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BIOLOGICAL TREATABILITY OF KRW ENERGY SYSTEMS GASIFIER PDU WASTEWATERS

by

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16. ABSTRACT The report gives results of bench-scale biological treatability tests with wastewaters produced from the KRW Energy Systems gasifier process development unit (KRW-PDU). Goals of the tests were to assess the biotreatability of these aqueous wastes and to develop data for correlations to establish a basis for designing a biooxidation process. An autotrophic activated sludge process was developed that utilized a mixed culture of nitrifying and sulfur-oxidizing bacteria for simultaneous thiocyanate biodegradation and nitrification. An ammonia-nitrogen concentration of > 250 mg/L and a thiocyanate concentration of 150 mg/L were bioxidized at a hydraulic residence time of 24 hours and at sludge ages between 60 and 150 days. Experimental tests at bioreactor temperatures below 20 C indicated that the nitrifying bacteria were severely impacted at a bioreactor temperature of 10 C, while the observed thiocyanate removal efficiency deteriorated at a mixed liquor temperature of 6 C. Elevated concentrations of chloride, fluoride, and boron in experimental wastewaters did not inhibit either nitrifying or sulfur-oxidizing bacteria in the activated sludge process. However, heavy metals were concentrated in the activated sludges, thought to be a consequence of the long sludge ages of the experimental process.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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Waste Water	Stationary Sources	
Water Treatment	Biological Treatability	
Coal Gasification	Bioxidation	13H
Oxidation		07B, 07C
Nitrification		

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ABSTRACT

Bench-scale biological treatability testing with wastewaters produced from the KRW Energy Systems gasifier process development unit (KRW-PDU) was conducted in order to assess the biotreatability of these aqueous wastes and to develop data for correlations that establish a basis for design of a biooxidation process. An autotrophic activated sludge process was developed that utilized a mixed culture of nitrifying and sulfur-oxidizing bacteria for simultaneous thiocyanate biodegradation and nitrification. An ammonia-nitrogen concentration of greater than 250 mg/L and a thiocyanate concentration of 150 mg/L was biooxidized at a hydraulic residence time of 24 hours and at sludge ages between 60 and 150 days. Experimental testing at bioreactor temperatures below 20°C indicated that the nitrifying bacteria were severely impacted at a bioreactor temperature of 10°C, while the observed thiocyanate removal efficiency deteriorated at a mixed liquor temperature of 6°C. Elevated concentrations of chloride, fluoride, and boron in experimental wastewaters did not inhibit either nitrifying or sulfur-oxidizing bacteria in the activated sludge process. However, heavy metals were concentrated in the activated sludges, and this was thought to be a consequence of the long sludge ages of the experimental process.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

Alk -- alkalinity
BOD -- biochemical oxygen demand
°C -- degrees Celsius
COD -- chemical oxygen demand
E -- activation energy
F/M -- food-to-microorganism ratio
GC-MS -- gas chromatography and mass spectrometry
HRT -- hydraulic retention time
°K -- degrees Kelvin
m/hr -- meters per hour
mg/L -- milligrams per liter
MLVSS -- mixed liquor volatile suspended solids
PDU -- process development unit
r -- correlation coefficient
R -- gas constant
SCN -- thiocyanate
SD -- standard deviation
SRT -- solids retention time
SVI -- sludge volume index
T -- temperature
TDS -- total dissolved solids
TKN -- total kjeldahl nitrogen
TOC -- total organic carbon
VSS -- volatile suspended solids
ZSV -- zone settling velocity
μg/L -- microgram per liter
μg/g -- microgram per gram

SYMBOLS

a' -- oxygen utilization coefficient
b -- endogenous decay coefficient
b' -- endogenous respiration coefficient
dF/dt -- volumetric rate of microbial assimilation
k_o -- maximum utilization coefficient (zero order)
k_1 -- first order utilization coefficient
k_e -- solids settleability coefficient

LIST OF ABBREVIATIONS AND SYMBOLS
(continued)

SYMBOLS

K_s -- concentration of susbstrate when rate of utilization is one half the maximum rate
m -- solids settleability coefficient
Q -- hydraulic throughput
R_r -- oxygen utilization rate
S -- substrate concentration
S_e -- effluent substrate concentration
S_o -- influent substrate concentration
U -- specific substrate utilization
V_a -- volume of bioreactor
V_w -- volume of mixed liquor wasted per unit time
X -- concentration of volatile suspended solids under aeration
X_e -- effluent volatile suspended solids
X_i -- initial suspended solids concentration
$(\Delta X/\Delta t)_t$ -- biomass production per unit time
Y -- sludge growth coefficient
σ -- temperature correction coefficient
θ -- detention time
θ_c -- sludge age

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SECTION 1

INTRODUCTION

Biological treatability studies were conducted on wastewaters from the KRW Energy Systems (KRW) gasifier, formally called the Westinghouse gasifier, process development unit (PDU) as part of a characterization program to develop design and environmental data for synthetic fuels plants based on KRW-type coal gasification technology. This report presents the results of the biooxidation study which was conducted through the cooperative efforts of Radian Corporation and Engineering-Science, Inc. to provide engineering and environmental data for the design of wastewater treatment systems for this and other similar coal gasification technologies.

1.1 PROJECT OVERVIEW

In 1982 the Department of Energy's Morgantown Energy Technology Center (METC), the Gas Research Institute (GRI), and the Environmental Protection Agency (EPA/AEERL) recognized the need for a program to provide wastewater treatment process design data for an ash agglomerating fluidized-bed gasification process. In response to this need, METC, GRI, and EPA entered into a joint program to develop wastewater treatment performance data, design parameters, and environmental characterization data from a series of bench-scale treatability tests with wastewaters from the KRW-PDU coal gasification process. The results of this experimentation produced a series of wastewater characterization and treatability documents which established basis of design data for the following wastewater treatment and reuse unit operations/processes:

- coagulation/clarification for removal of small diameter (<2 microns) carbon particles (fines) present in the wastewaters after bulk settling of dense solids suspensions found in the PDU quench liquors/gas cooling condensates;
- chemical conversion and fixation of cyanide to less toxic forms;
- steam stripping for removal of dissolved acid gases and ammonia;
- activated sludge for ammonia, thiocyanate, and organic carbon removal; and
- concentration of treated effluents by low temperature and high temperature evaporation processes.

This report serves as the basis-of-design document for an autotrophic activated sludge process which was developed to treat process wastewaters from an ash agglomerating fluidized-bed gasification process. The technology also is generally applicable to the treatment of process wastewaters from entrained-bed gasifiers and should be viewed as a technology innovation for treatment of low tar, oil, and phenol coal gasification quench liquors and gas cooling condensates.

1.2 OBJECTIVES

The biological treatability tests were performed using wastewater from the KRW gasifier PDU. The primary objectives of the study were:

- To determine the feasibility of biological treatment of KRW-type gasifier wastewaters using mixed populations of heterotrophic and obligate autotrophic bacteria for degradation of organic carbon, ammonia, and thiocyanates.
- To obtain data for the determination of preliminary design parameters for an activated sludge process to treat KRW-type gasifier wastewater.

Bench-scale laboratory studies using continuous-flow bioreactors were conducted with the KRW wastewater. These studies were preceded by an initial period of activated sludge acclimation that established a representative microbial population for treatability testing. The continuous-flow biooxidation reactors were operated at different biological solids retention times and substrate loadings in order to establish the biokinetics of the activated sludge process. The impact of any toxic or inhibitory substances that may have been present in the KRW wastewater were investigated during treatability testing.

The effects of temperature and nonsubstrate ions on microbial activity were investigated using biooxidation test reactors and activated sludges acclimated during continuous-flow testing. Alkalinity and pH considerations also were investigated during continuous flow testing.

These data were used to develop a basis-of-design for an activated sludge process to treat KRW-type gasifier wastewater.

1.3 REPORT CONTENT

This document is organized into seven sections. Section 3 presents a review of process microbiology, and Section 4 discusses the characteristics of the wastewaters used during experimental testing. Section 5 presents the experimental approach used to achieve microbial acclimation and to assess steady-state performance data. Section 6 presents the results of the steady-state evaluation and the determination of process design parameters. Section 7 presents the results of microbial stress studies regarding both temperature impacts and the effects of nonsubstrate ions on microbial activity. Section 2 presents study conclusions. Data presentations and quality assurance information are detailed in the Appendices.

SECTION 2

CONCLUSIONS

Conclusions that can be drawn from the information obtained during steady-state and microbial stress testing of activated sludges used for the biooxidation of pollutants in the KRW-PDU wastewater are summarized as follows:

- KRW wastewaters pretreated by steam stripping for ammonia reduction and acid gas removal can be successfully treated biologically with the activated sludge process. An ammonia-nitrogen concentration of 285 mg/L and a thiocyanate concentration of 150 mg/L can be biooxidized on a long-term basis at neutral pH conditions with a mixed culture of nitrifying and sulfur-oxidizing bacteria.

- Concentrations of 3000 mg/L chloride, 285 mg/L fluoride, and 150 mg/L boron in the KRW wastewater did not inhibit either the nitrifying or sulfur-oxidizing bacteria in the activated sludge process. The presence of low levels of free and complexed cyanide in the KRW wastewater did not have an adverse impact on ammonia or thiocyanate removal during biooxidation. Consequently, an autotrophic activated sludge process can be used to treat similar wastewaters derived from the gasification of different coals. The process may also be applicable to the treatment of wastewaters from other fluid- and entrained-bed gasifiers that produce aqueous wastes with chemistries similar to the experimental wastewater compositions.

- A study of temperature effects on the biodegradation of ammonia and thiocyanate indicated that the nitrifying bacteria were severely impacted at a bioreactor operational temperature below 10°C. This effect was thought to be largely the result of substrate (ammonia) inhibition. The observed thiocyanate removal efficiency deteriorated at a bioreactor operational temperature below 6°C. However, there was no apparent reduction in thiocyanate biodegradation as the temperature was reduced until this temperature was reached, despite elevated levels of ammonia in the test bioreactor.

- Although the settleabilities of the activated sludges were generally good, the apparent activated sludge settling quality as measured by the zone settling velocity and the sludge volume index showed a deterioration at higher bioreactor sludge ages. Operational sludge ages for the experimental biooxidation process varied between 60 and 150 days. Generally, these sludge ages were considered necessary to maintain system stability for complete nitrification and to minimize sludge production.

- Heavy metals were concentrated in the activated sludges during experimental testing. However, the degree of bioaccumulation associated with the presence of metal-cyanide complexes in the wastewater could not be determined from the experimental data. The removal during biooxidation treatment of extractable/chromatographable organics identified by GC-MS analysis was inconclusive. The study did not provide a determination of the fate of organics in the autotrophic activated sludge process because of contradictory results regarding the nature of the organics in the aqueous and solid phases of the process.

SECTION 3

BIOLOGICAL TREATMENT FOR THE REMOVAL OF AMMONIA AND THIOCYANATES

Biological oxidation treatability studies on KRW-PDU wastewaters were conducted to obtain data for the determination of design parameters for the treatment of contaminated quench liquors and gas condensates produced during coal gasification. The characteristics of the KRW-PDU wastewater were such that biological oxidation of nitrogen species (i.e., ammonia and thiocyanate) is the most important consideration because the organic pollutant content of the wastewater is low. The study involved an examination of aerobic chemoautotrophic cultures which were utilized for the biodegradation of ammonia and thiocyanate. Previous research has indicated that a variety of aerobic bacteria are capable of degrading thiocyanates during the biooxidation of coke oven wastewaters and fixed-bed coal gasification raw product gas quench condensate. One of the purposes of this study was to examine the feasibility of developing an obligate autotrophic population of bacteria that could perform similar metabolic functions in order to achieve thiocyanate degradation and attain simultaneous nitrification in a single bioreactor. The following subsections provide background for the microbiology examined in this program.

3.1 CHEMOAUTOTROPHS

Chemoautotrophic organisms are dependent on chemical energy sources and employ carbon dioxide as the principal carbon source. The use of CO_2 as a carbon source by chemotrophs is always associated with the ability to use reduced inorganic compounds as energy sources. This ability is confined to the bacteria and occurs in a number of specialized groups that can use reduced nitrogen compounds (NH_3, NO_2^-), ferrous iron, reduced sulfur compounds (H_2S, $S^=$, $S_2O_3^=$), or H_2 as oxidizable energy sources.

By definition, a chemoautotroph must possess two special biochemical capacities: the ability to derive Adenosine Triphosphate (ATP) and reducing power from the oxidation of a reduced inorganic compound, and the ability to use CO_2 as its principal or sole source of carbon, an attribute that implies possession of specialized enzymatic machinery. The two groups of chemoautotrophic bacteria examined during the study were the nitrifying bacteria and sulfur oxidizing bacteria.

The nitrifying organisms fall into two separate physiological groups: bacteria that oxidize ammonia to nitrite and bacteria that oxidize nitrite to nitrate. The most common ammonia oxidizer in soil is Nitrosomonas and among the nitrite oxidizers, the most common soil form is Nitrobacter. The chemoautotrophic sulfur-oxidizing bacteria are placed in a single genus, Thiobacillus. These organisms can grow at the expense of elemental sulfur, and many can use thiosulfate as well. Their growth in mineral media is rapid relative to that of nitrifiers; generation times as short as four to five hours have been recorded.

3.1.1 Nitrifying Bacteria

The nitrifying bacteria, Nitrosomonas and Nitrobacter, are able to fix carbon dioxide at the expense of energy obtained from the oxidation of ammonia to nitrites and nitrates. The cell walls of these bacteria consist of numerous polypeptides (long-chain proteins) and fatty acids. The cell membrane is considered an important factor for the nitrification process according to the following:

- Oxidation of ammonia and nitrite takes place on the cell surface and the rate of nitrification is proportional to the amount of cytochrome present in the cell membrane.

- The two organisms reproduce differently (fission for Nitrosomonas and budding for Nitrobacter) and consequently, their growth kinetics are different.

Inhibitors to nitrification include metal binding compounds, protein binding compounds, inhibitors of electron transport, short-chain alcohols, amines, and certain carbon free radicals (e.g., CCl_3). The specific types of inhibition are discussed in Table 3-1. The nature of this inhibition will take the following forms:

- Physiological-substrate or product tolerance limits,
- Metabolic-respiration, and
- Growth suppression.

Although the activities of Nitrosomonas and Nitrobacter may be inhibited by certain substances, the extent of such inhibition may be different for each species. The more complicated Nitrosomonas enzyme system, needed to produce a nitrogen oxyanion (i.e., $N^{\equiv}$ to N^{+++}), is more susceptible to inhibition than the simpler enzyme system of Nitrobacter needed to change the oxidation state of the oxyanion (i.e., N^{+++} to N^{+++++}). For this reason, and because Nitrobacter would have no substrate without Nitrosomonas producing it first, Nitrosomonas is considered to be the more important link in the oxidation chain (Neufeld et al. 1979).

The process of converting ammonia to nitrates involves the destruction of alkalinity, which, in turn, means a drop of pH; and it follows, an inhibition of the nitrification reaction. From the equations presented below, it can be seen that two equivalents of alkalinity are consumed per equivalent of ammonia-nitrogen oxidized. Theoretically, 7.14 mg of total alkalinity are destroyed per mg of ammonia-nitrogen oxidized to nitrate.

$$NH_4^+ + 2O_2 \longrightarrow NO_3^- + 2H^+ + H_2O$$

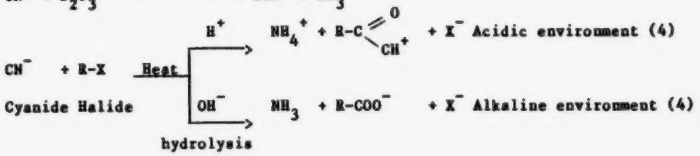
$$2H^+ + 2HCO_3^- \longrightarrow 2H_2O + 2CO_2$$

TABLE 3-1. INHIBITION OF NITRIFICATION

INHIBITOR	EFFECTS AND COMMENTS	REFERENCES
Unionized ammonia	Suppresses metabolic rates of both bacteria by:	
	1. Inhibiting the oxidation of ammonia to nitrate by Nitrosomonas within the range of 10 - 150 mg/L.	Aleem, et al., 1957; Anthonisen, et al., 1976; and Neufeld et al., 1979.
	2. Inhibiting the oxidation of nitrite to nitrate by Nitrobacter within the range of 0.1 - 1.0 mg/L.	
Nitrite (1)	1. Depresses both growth and respiration of Nitrosomonas by inhibiting ammonia-nitrogen oxidation between the concentrations of 200 - 2,500 mg/L.	De Marco et al., 1967.
	2. Inhibits its own oxidation when an excess amount is formed.	Butt and Lees, 1960.
Undissociated Nitrous Acid (2)	1. Inhibits nitrifying bacteria respiration.	Engel and Alexander, 1958.
	2. Inhibits nitrite oxidation at the concentration of 0.22 - 0.28 mg/L.	Anthonisen et al., 1976.
Nitrate	1. Has no effect on the ammonium ion oxidation.	De Marco et al., 1967.
	2. Inhibits nitrite oxidation at high oxygen level, but stimulates it at low oxygen level (3).	Butt and Lees, 1960.
pH	The optimum pH for Nitrosomonas is pH 8.0 and for Nitrobacter is pH 7.7 (pure culture). Since the wastewater contains a mixed culture of nitrifying bacteria, the optimum nitrification efficiency occurs at a pH of 8.4 (assuming no unionized ammonia toxicity), and the range for nitrification lies between 6.5 - 9.5. The pH affects nitrification according to the following:	Huang and Hopson, 1973.
	1. Reducing the nitrification efficiency to 50% and 30% of the optimum at the pH values of 7.0 and 6.5, respectively.	
	2. Decreasing the metabolic rate to about 50% of the optimum at the pH values of 6.2 and 9.6.	Loveless and Painter, 1968.
	3. Increasing the unionized ammonia level in the alkaline range.	Prakasam and Loehr, 1972
	4. Increasing the concentration of undissociated HNO_2 with a decrease in pH.	Butt and Lees, 1960.

(continued)

TABLE 3-1. (continued)

INHIBITOR	EFFECTS AND COMMENTS	REFERENCES
Temperature	Temperature acts as a modifying factor for nitrification. The rate of nitrification increases with an increase in temperature within the range of 5 - 30°C. The magnitude of inhibition decreases with an increase in nitrification rate.	Hochster and Quastel, 1963.
Dissolved oxygen	1. The rate of oxygen uptake increases with the concentration of inhibitor in a logarithmic fashion.	Lees, 1952.
	2. Low oxygen levels inhibit growth rate and population growth.	Skinner and Walker, 1961.
Heavy metals	The inhibition of nitrification in the presence of heavy metals is due to the chelation and precipitation of cell proteins. The metals: 1. Inhibit metabolic rate by interfering with enzyme action. 2. Inhibit growth by altering the membrane permeability and blocking the uptake of essential nutrients.	Hochster and Quastel, 1963.
Aromatic hydrocarbons	Inhibit ammonia oxidation.	Neufeld, et al., 1979; Hockenbury and Grady, 1977.
Cyanide	CN^- is a strong base and can form thiocyanate, the ammonium ion, and unionized ammonia according to the reactions: $CN^- + S_2O_3^{2-} \longrightarrow SCN^- + SO_3^{2-}$  $CN^- + R\text{-}X \xrightarrow{\text{Heat}} \xrightarrow{H^+} NH_4^+ + R\text{-}C(=O)CH^+ + X^-$ Acidic environment (4) Cyanide Halide $CN^- + R\text{-}X \xrightarrow{\text{Heat}} \xrightarrow[\text{hydrolysis}]{OH^-} NH_3 + R\text{-}COO^- + X^-$ Alkaline environment (4)	Hochster and Quastel, 1963.
	1. CN^- inhibits ammonia and nitrite oxidation by restricting the electron transport system. $2(10^{-5})$ moles of cyanide reduced ammonia oxidation by 42% nitrite oxidation by 50%. $1(10^{-4})$ moles of cyanide reduced 97% of the ammonia oxidation and 79% of the nitrite oxidation.	Tomlinson et al., 1966; Anderson, 1965.

(continued)

TABLE 3-1. (continued)

INHIBITOR	EFFECTS AND COMMENTS	REFERENCES
	2. Inhibition is favored by a high pH.	
Thiocyanates	SCN^- inhibits metabolism. The inhibition is 75% of the optimum at pH 6.0 and 2 (10^{-2}) Moles.	Hochster and Quastel, 1963.
Chlorates	ClO_3^- will destroy cytochrome 551 of the electron transport system and all chlorates:	Lees and Simpson, 1957.
	1. Inhibit growth.	
	2. Inhibit respiration. $2(10^{-3})$ Moles inhibits the respiration of Nitrobacter by 80%.	
Halides	Halides inhibit respiration and nitrogen oxidation, but the effect is mild.	Hochster and Quastel, 1963.

(1) Nitrite inhibition is not serious because this compound is unstable.

(2) This inhibition is reversible and is not considered a serious problem because HNO_2 is a weak acid and can be neutralized easily by the buffer capacity of the wastewater. The operational pH range of the nitrification system creates an unfavorable condition for the formation of HNO_2.

(3) Since the oxygen level during nitrification is usually not higher than 2.0 mg/L, inhibition by nitrate should not be significant.

(4) The reactions require heat and may not take place at room temperature.

Studies with both air and oxygen suspended growth nitrification processes indicated no apparent initial uptake of ammonia-nitrogen by nitrifiers; therefore, the phenomenon of bioadsorption is not a characteristic of the nitrification process. No lag in the rate of nitrification was observed when the return sludge population was high in nitrifiers. As the residual ammonia concentration decreased, the rate of nitrification remained constant, which is indicative of a zero-order reaction. The rate of nitrification is defined as the weight ratio of ammonia-nitrogen oxidized per day to the MLVSS under aeration. Since nitrification is a consecutive reaction involving two different microorganisms, it is not possible that the reaction could actually be zero-order, but considering the ammonia-nitrogen concentrations normally found in sewage and industrial wastes, the overall appearance of zero-order is understandable. The nitrifiers have lower reproduction rates than the organic-assimilating organisms and have a difficult time competing in the same environment (Huang and Hopson 1974). In an activated sludge system, the nitrifiers, because of their lower reproduction rate, may be wasted from the system faster than they can reproduce, thereby inhibiting successful nitrification. Consequently, insufficient nitrification will result unless the sludge wastage rate is lowered to accommodate the nitrifiers' requirements. The sludge wastage rate is usually controlled to maintain a sufficient sludge age in the system for the desired degree of nitrification.

The theoretical oxygen requirement, based on the biochemical equations of nitrification, is defined as 4.57 mg of oxygen required per mg of ammonia-nitrogen nitrified. It is assumed that this oxygen demand must be satisfied by atmospheric molecular oxygen, furnished and dissolved by conventional aeration equipment.

It is difficult to distinguish experimentally between that oxygen required for nitrification and that oxygen required for organic BOD oxidation. The oxygen uptake rate as measured by the dissolved oxygen probe will reflect total oxygen requirements for both BOD and ammonia oxidation.

Nitrifying bacteria have more specific environmental requirements than do the heterotrophic bacteria responsible for carbon removal. These environmental requirements include specific factors which influence the metabolism and biosynthesis of the microorganisms. In particular, attention is given to pH, mixed liquor dissolved oxygen concentration, temperature, and the possible presence of toxic materials.

The nitrifiers are sensitive microorganisms that are subject to severe upsets should environmental factors be unfavorable. Compounds which are most often associated with toxicity to nitrifiers include heavy metals, cyanides, halogenated compounds, phenols, mercaptans, and amines. The nitrifiers also are subject to substrate inhibition. Both Nitrosomonas and Nitrobacter have been inhibited by the presence of free ammonia and free nitrous acid at varying concentration levels (Anthonisen et al. 1976). Substrate inhibition which involves a complex relationship between inhibition thresholds and pH is one of the principal concerns of this study.

The presence of trace amounts of inhibitory constituents may not prevent nitrification, but could lower the reaction rate substantially if the rate of biosynthesis is retarded. Many of the organic compounds which inhibit the nitrification reaction also are inhibitors of bacterial metabolism, in general. The most potent inhibitors are sulfur-containing compounds since they chelate metals and thus inhibit enzymes requiring metals for activation (Tomlinson et al. 1966).

The assertion that low biochemical or chemical oxygen demand concentrations are required to establish nitrification is incorrect. The concentration of BOD in the wastewater has no direct relationship to the nitrification process. (There appears to have been a belief in the past that organic matter had a deleterious effect on the activity of autotrophic bacteria.) The fact that nitrifying bacteria are autotrophic does not mean that they cannot take up organic compounds from a wastewater and incorporate them into cell material (Hockenbury and Grady 1977). Consequently, concern over the presence of organic matter should be focused on specific compounds that might cause inhibition.

Metal ions also are of concern because nitrifying bacteria are more susceptible to heavy metal toxicity than the bacteria responsible for oxidation of the carbonaceous biochemical oxygen demand (Loveless and Painter 1968). In general, copper, nickel, zinc, and chromium will have a detectable effect on purification by the activated sludge process, namely, to increase turbidity and to reduce nitrification. Usually, the concentration of metals necessary to inhibit nitrification in activated sludge will be much higher than that required to give the same effect in pure culture (Braam and Klapwijk 1981).

3.1.2 Sulfur-Oxidizing Bacteria

Members of the genus Thiobacillus grow aerobically with inorganic sulfur compounds as the energy source. All members of the genus with the exception of T. novellus are strict autotrophs. Most species of Thiobacillus grow best with thiosulfate as the energy source, but sulfide, sulfur, and thiocyanate also can be used by certain species for growth. These bacteria grow best between the pH range of 6.0 and 7.6 and the temperature range of 25°C to 35°C. The optimum pH range for thiocyanate degradation by bacteria is between pH 6.7 and pH 7.2 (Neufeld and Valiknac 1978). An alkaline pH tends to inhibit the biodegradation of thiocyanate and this is the result of a physiological inhibition (the upper tolerance limit of the bacteria) and not a toxic effect. Temperatures above 37°C inhibit the growth of Thiobacillus.

Thiocyanates serve as both a source of energy and as a source of carbon and nitrogen for Thiobacillus thiocyanooxidans (Youdatt 1954). It is hypothesized that thiocyanate is first biochemically hydrolyzed to cyanate and sulfide as follows:

$$SCN^- + H_2O \longrightarrow HS^- + HCNO$$

and cyanate is then hydrolyzed further to carbon dioxide and ammonia:

$$HCNO + H_2O \longrightarrow NH_3 + CO_2$$

and sulfide is oxidized to sulfate:

$$HS^- + 2O_2 \longrightarrow HSO_4^-$$

Based on laboratory observations, the overall reaction is:

$$SCN^- + 2H_2O + 2O_2 \longrightarrow CO_2 + SO_4^= + NH_4^+.$$

It is not known whether T. thiocyanooxidans are responsible for the conversion of sulfide to sulfate. However, T. thiooxidans will oxidize either sulfur or thiosulfate to sulfate and this reaction is accompanied by a considerable generation of hydrogen ions. T. thiooxidans will continue to grow until the pH has fallen to approximately pH 1.0. Thiobacillus thioparus, on the other hand, grows best under neutral conditions, and its development ceases at a pH of approximately 5.0. Continuous culture systems operated at a pH of between 6 and 7 attained virtually complete thiocyanate removal at influent thiocyanate levels of 1,000 mg/L. However, these same continuous culture systems operating at a pH of 5 or 8 produced poorer quality effluents and some degree of process instability (Neufeld et al. 1981).

Metal ions caused inhibition of substrate removal kinetics in the oxidation of thiosulfate by an authentic strain of T. thiooxidans. The calculated values of the inhibitor concentration for cadmium, copper, lead, silver, and zinc were 16, 0.5, 2, 3, and 33 mg/L, respectively. Only a slight additive effect on inhibition was apparent with the presence of all of these metal ions. A mixed culture of thiosalt-oxidizing bacteria was found less sensitive to heavy metal inhibition (Silver and Dinardo 1981).

It is believed that the toxic effect of a given metal is correlated with the concentration of free metal ions in the wastewater rather than the total metal concentration (Braam and Klapwijk 1981). The concentration of metal ions in solution is a function of the activated sludge mixed liquor concentration: increasing the MLVSS concentration will cause a decrease in the metal ion concentration. The concentration of free metal ions in solution is strongly correlated with pH. For instance, the free copper concentration will increase with decreasing pH.

3.2 PROCESS CONSIDERATIONS

Reliable operation and control of the activated sludge process for thiocyanate removal and nitrification requires an understanding of microbial growth kinetics. For the nitrification process to occur, the growth rate of the total activated sludge biomass must be less than the maximum growth rate of the nitrifying bacteria. If this condition is met, a nitrifying population could be permanently established in the activated sludge process. If this condition is not met, the nitrifying bacteria would be wasted from the system at a rate faster than their maximum ability to grow.

The concept of biological solids retention time (SRT) or sludge age is the appropriate parameter for design and control of nitrifying activated sludge systems. The sludge age is defined as follows:

$$\theta_c = \frac{X_t}{(\Delta X/\Delta t)t} \qquad (3\text{-}1)$$

where:

θ_c is the biological SRT, days;

X_t is the biomass under aeration (MLVSS), grams; and

$(\Delta X/\Delta t)_t$ is the quantity of biomass withdrawn daily, including those solids purposely wasted as well as those lost in the effluent, grams/day.

Under steady-state conditions, the SRT is equal to the reciprocal of the net specific growth rate (mg VSS produced per day per mg MLVSS under aeration). For a nitrifying activated sludge system, the sludge age must be greater than the reciprocal growth rate of the nitrifying bacteria at a given temperature. The choice of a design and operating value of the sludge age fixes only the total system biomass for the wastewater and allows design tradeoffs between aeration tank volume and MLVSS concentration. Thus, nitrification may be achieved at short hydraulic retention times provided that aeration tank MLVSS concentration and solids wasting practices are chosen correctly to maintain a selected value of the SRT.

The KRW-PDU treatability study was conducted with a one-sludge completely mixed continuous-flow bioreactor. The one-sludge nitrifying activated sludge system is a modification of the conventional activated sludge process. This modification is achieved by increasing the operating solids retention time (SRT) of the overall process to a value greater than the minimum value of the sludge age for the nitrifying bacteria. This will result in the reduction of the food-to-microorganism ratio of the organic-carbon-utilizing heterotrophic bacteria in the bioreactor. Thus, carbon removal and ammonia oxidation occur simultaneously in the same reactor, and the overall system growth rate is determined by the growth kinetics of the nitrifying bacteria.

The success of this approach largely depends on the ability of the various heterotrophic and autotrophic bacteria in the activated sludge to degrade the organic and inorganic compounds in the KRW wastewaters. The degree to which nitrification may be inhibited will depend on the relative toxicity of the KRW wastewaters and their resistance to biodegradation.

SECTION 4

WASTEWATER CHARACTERIZATION

This section discusses wastewater sample collection and defines the characteristics of the KRW-PDU wastewaters used during biological treatability testing. Samples were obtained by Radian Corporation under contract with the Gas Research Institute (GRI) during a test burn of the PDU by KRW Energy Systems, Inc. at Waltz Mill, Pennsylvania in June of 1983.

4.1 SAMPLE COLLECTION

Wastewater samples for the biological treatability study were collected during the Pittsburgh No. 8 test burn of the KRW-PDU conducted between June 18th and 22nd, 1983. Twelve drums each of the quench recycle water (R-12) and the product gas cooler recycle water (R-15) streams were collected on June 21, 1983 between the hours 1025 and 2315. A one-to-one blend of the R-12 and R-15 samples provided a representative mix of the PDU wastewater effluent. All samples were collected and cooled in reconditioned, removable lid drums fitted with polyethylene liners. Each drum was purged with nitrogen gas prior to filling. During the period of wastewater collection, grab samples of each individual stream were obtained at approximately three hour intervals. These samples were returned to the Radian on-site laboratory and immediately analyzed for pH, conductivity, ammonia, thiocyanate, sulfide, and sulfite. In addition, equal amounts of each of the individual grab samples were combined to form a single composite for each stream. These composites were analyzed on-site for cyanide and preserved for additional analysis at the Radian Analytical Services Laboratories in Austin, Texas. All analyses were completed within seven days of sample collection. Sample handling and analysis procedures are presented in Appendix L and on-site/off-site analytical results are depicted in Appendix M to this report.

The wastewater drums were shipped to Austin and stored upon arrival (four days after collection) in the Radian Warehouse cooler at approximately $4^{o}C$. One drum of wastewater for each sample stream was tested to determine sample stability during shipping. The results of these analyses are also presented in Appendix M.

4.2 BIOREACTOR FEEDWATER QUALITY

The wastewaters for biological treatability testing were steam-stripped without pH adjustment before being transported to the study site in plastic-lined drums. During steady-state testing, approximately one drum of wastewater was used per week of bioreactor operation. Characterization statistics for the pretreated KRW-PDU wastewaters, determined from the analysis of sample drums used during the steady-state testing, are presented in Table 4-1. These data characterize a wastewater that is low in total organic carbon (TOC) and has moderate to high levels of ammonia (NH_3-N) and thiocyanates (SCN). The observed magnitude of the chemical oxygen demand (COD) includes contributions from both the organic carbon and SCN concentrations of the wastewater.

Summary statistics for the observed bioreactor feedwater quality during the period of steady-state treatability testing is presented in Table 4-2. These data which are presented in Appendix A characterize the actual influent wastewater quality to the test bioreactors during steady-state operation. The influent feedwaters were spiked with low levels of ammonia in the form of ammonium chloride (NH_4Cl) to raise the equilibrium ammonia-nitrogen levels of the wastewater to the design level of 250 mg/L NH_3-N. However, the overall chemical characteristics of the feed wastewaters are the same as that of the sample drums.

TABLE 4-1. KRW-PDU WASTEWATER CHARACTERIZATION[a]

Parameter	Mean (mg/L)	Range (mg/L)	Standard Deviation (mg/L)	Number of Data Points
pH	7.23[b]	5.67 - 8.21[b]	0.80[b]	18
TDS[c]	203	144 - 250	31	18
NH_3-N	187	165 - 230	16	18
COD	207	110 - 310	57	18
TOC	58	49 - 80	10	18
Free CN	0.56	0.22 - 1.18	0.32	11
Total CN	1.4	0.8 - 2.2	0.5	12
SCN	136	117 - 150	8	18

[a] Wastewaters were steam stripped without pH adjustment. These are analyses of the sample drums delivered to the site of the biological treatment tests.

[b] pH units.

[c] at 180°C.

TABLE 4-2. BIOREACTOR FEEDWATER QUALITY[a]

Parameter	Mean (mg/L)	Range (mg/L)	Standard Deviation (mg/L)	Number of Observations
TOC	38	29 - 44	4	42
COD	178	145 - 242	25	39
BOD_{20}[b]	1,163[c]	917 - 1,539	238	5
NH_3-N	253	238 - 270	7	66
NO_3-N	<0.5[d]	<0.5 - 3.4	0.68	36
NO_2-N	<0.1[d]	<0.1 - 0.21	0.03	36
SCN	130	116 - 150	9	38
Total CN	1.19	0.8 - 1.56	0.2	30
Total P	4.95	2.5 - 6.0	1.36	6
TSS	5	<1 - 34	5	43
VSS	2	<1 - 17	3	43
TDS	294	220 - 490	59	37
Alkalinity ($CaCO_3$)	57	13 - 191	36	41
pH	6.91	5.4 - 8.15	0.51	133

[a] Wastewater quality of actual reactor influent during the study period (07/29/83 - 11/17/83).

[b] Unfiltered.

[c] Mean BOD_5 equals 252 mg/L.

[d] Values are median of data.

Data for feedwater 20-day biochemical oxygen demand (BOD_{20}) are also presented in Table 4-2. These BOD_{20} values were representative of a seeded influent sample, and the observed experimental concentrations were determined to be approximately 75 percent of the theoretical (ultimate) oxygen demand of the KRW wastewater as estimated from the average ammonia, thiocyanate, and organic carbon concentrations.

A plot that depicts the observed progress of the biochemical oxygen demand of the KRW-PDU wastewater (bioreactor influent) is presented in Figure 4-1. This curve represents a typical BOD relationship for the nitrification reaction. However, the observed lag was surprising given that the seed nitrifier population was obtained from a well-acclimated culture of microorganisms that were capable of treating the KRW wastewater to high levels. The observed lag may have been due more to mass transfer limitations during the BOD reaction than to kinetic effects characteristic of a lag in nitrifier population growth rates. Nevertheless, the apparent oxygen utilization in the early portion of the BOD curve can be explained by the oxygen demand associated with the organic carbon and thiocyanate components of the KRW wastewater, and little nitrification appears to have occurred until after ten days of BOD bottle incubation.

Thiocyanate contributes the largest portion of the chemical oxygen demand (COD) of the KRW wastewater. The oxygen demand produced by the ammonia in the wastewater is not accounted for in the COD test because dichromate is not reduced by ammonia or any ammonia liberated from the breakdown of proteinaceous matter. Thiocyanate exists at elevated concentrations in the KRW wastewater.

Point-in-time wastewater environmental characterization data for influent and effluent bioreactor samples are presented in Table 4-3. These data are supplemental to the statistical characterization information presented previously. They indicate that the KRW wastewater contains low levels of fluoride, chloride, sulfate, and reduced sulfur compounds in addition to the

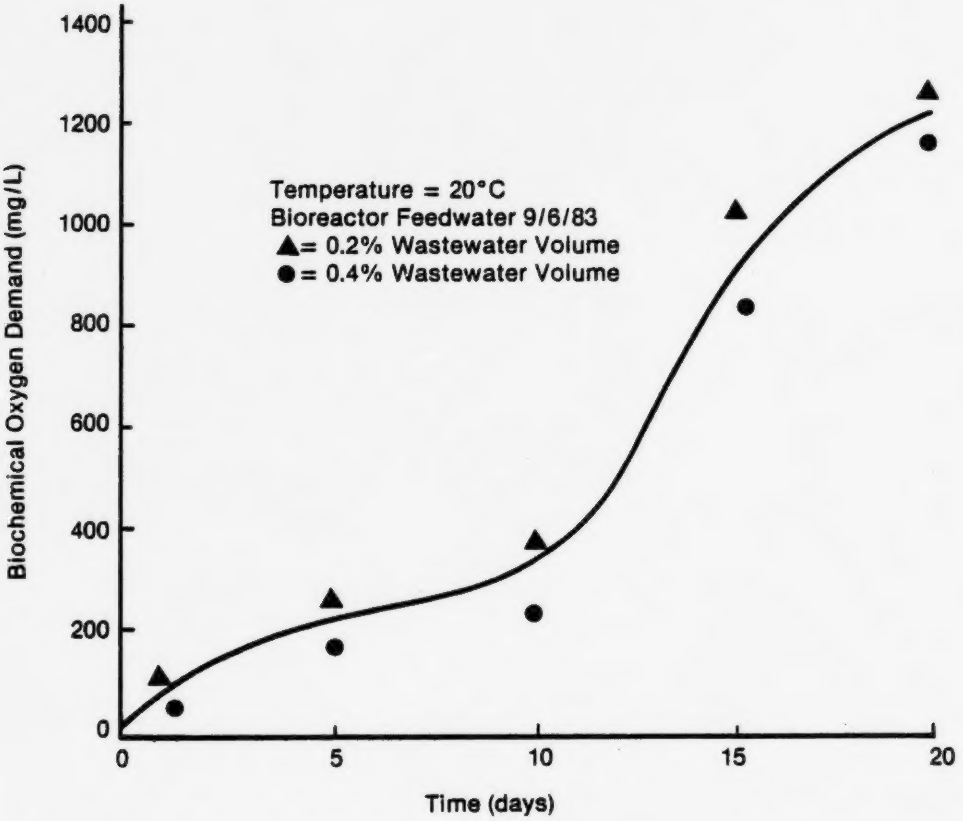


FIGURE 4-1. Wastewater biochemical oxygen demand

TABLE 4-3. ENVIRONMENTAL CHARACTERIZATION OF BIOREACTOR FEEDWATER

Parameter[a]	Sample 1[b]	Sample 2[b]
pH (pH units)	7.25	7.45
Conductivity (umhos/cm at 25°C)	2,250	2,400
Carbonate alkalinity as $CaCO_3$	0	0
Bicarbonate alkalinity as $CaCO_3$	123	79
Total solids	1,100	880
Total dissolved solids	490	260
Total suspended solids	23	5
Total settleable solids (mL/L)	<0.1	<0.1
Chloride	347	475
Cyanide	0.99	1.23
Fluoride	19	—[c]
TKN	280	—
Ammonia as N	225	249
Thiocyanate	150	131
Sulfide as S	<1	5
Sulfite as SO_3	2	2.5
Sulfate as SO_4	244	227
Phenol	<0.01	<0.005
TOC	32	49
TIC	30	10
COD	90	163
Oil and grease	<1	<1

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[a] All results as mg/L except as noted in parentheses.

[b] Samples of bioreactor feedwater collected 9/5 and 9/22/83 during steady-state operation.

[c] Blank means parameter not analyzed.

other pollutants already discussed. The probable feedwater BOD_5 concentration is approximately 250 mg/L. The observed magnitudes for the total Kjeldahl nitrogen (TKN) of the bioreactor feedwater samples presented in Table 4-3 are probably higher than the actual concentrations that would characterize this wastewater. The wastewater analyses conducted during treatability testing generally found the organic nitrogen levels in the KRW wastewater to be less than 30 mg/L which equates to an average TKN of approximately 280 mg/L for the bioreactor feedwater.

The results of trace element analyses for both influent and effluent bioreactor samples are presented in Table 4-4. These data indicate that the majority of the trace metals are present at low concentrations. Elements with measurable concentration levels are boron, potassium, magnesium, and phosphorus. Phosphorus is normally present at low concentrations in the KRW wastewater; however, it was added to the bioreactor feedwater as a supplemental nutrient for microbial cell growth.

The GC-MS analysis of the KRW wastewater produced the organic data presented in Table 4-5. Each of these pollutants was present at low concentrations in the KRW wastewaters and also was detected in the biologically treated effluents.

The concentrations of major biodegradable pollutants (i.e., NH_3-N and SCN) in the KRW-PDU wastewaters are considered representative of pretreated process wastewaters generated from a commercial KRW-type coal gasification facility. There will presumably be differences in the concentrations of chloride, fluoride, sulfur species, and certain metals, depending on coal-type. However, these differences are not expected to impact greatly the performance of the biooxidation process when treating these wastewaters.

TABLE 4-4. TRACE ELEMENTS IN BIOREACTOR FEEDWATER

Element[a]	Sample 1[b]	Sample 2[b]
Silver	<0.002	0.002
Aluminum	1.6	0.66
Arsenic	<0.06	<0.08
Boron	11	13
Barium	0.45	0.29
Beryllium	<0.0005	<0.001
Cadmium	0.003	<0.002
Cobalt	0.007	<0.006
Chromium	0.004	<0.001
Copper	0.016	0.047
Iron	0.56	0.63
Mercury	<0.03	<0.03
Potassium	7.9	10
Magnesium	6.7	6.1
Manganese	0.027	0.018
Molybdenum	<0.002	0.004
Sodium	9.4	9.4
Nickel	0.012	<0.003
Phosphorus	5.1	6.3
Lead	<0.084	<0.084
Antimony	<0.032	<0.035
Selenium	<0.08	<0.08
Silicon	11	13
Titanium	<0.005	0.032
Thallium	<0.091	<0.091
Vanadium	0.005	0.005
Zinc	0.015	0.018

[a] All results as mg/L.

[b] Samples of bioreactor feedwater collected 9/5 and 9/22/83 during steady-state operation.

TABLE 4-5. GC-MS RESULTS FOR KRW-PDU WASTEWATER

Compound[a]	Sample Analysis[b]
N-methylpyrole	2.7
Naphthalene	0.5
Benzothiazole	4.5
4-Methoxycycloheptanone	0.6
Biphenyl ether	0.4
Carbazole	3.6
Hexadecanoic acid	1.3
2-Methylthiobenzothiazole	ND[c]
Alkylbenzenesulfonamide	26

[a] All values as µg/L.

[b] Sample of bioreactor feedwater collected 9/22/83 during steady-state operation.

[c] ND = Not detected in influent but found in effluent.

SECTION 5

EXPERIMENTAL APPROACH

This section describes the experimental approach used to develop design data for the activated sludge process. The section consists of the following:

- a description of bench-scale biological treatability testing equipment,
- a discussion of data reduction and validation procedures, and
- a discussion of the acclimation procedures used to develop a microbial culture.

5.1 BENCH-SCALE TREATABILITY EQUIPMENT

The reactor required for wastewater biological treatment testing and the development of design criteria for the activated sludge process consists of an aeration chamber and settling compartment plus associated apparatus to monitor substrate removal efficiencies, oxygen uptake, pH, solids settleability, and excess sludge production.

5.1.1 Bench-scale Activated Sludge System

Continuous-flow reactor systems were used in the laboratory to determine the applicability and kinetics of the activated sludge process. The continuous-flow laboratory system was designed to provide a steady supply of raw wastewater through a biological reactor and to permit a continuous withdrawal of the treated effluent.

The system shown in Figure 5-1 combines both aeration chamber and upflow clarifier into a single unit and was found to be useful in the laboratory for bench-scale experimentation because it eliminates the need for a separate clarifier and an additional pump to control the return sludge. The test reactor was made of plastic and had an aeration chamber volume of ten liters.

The pumps used during the laboratory bench-scale study were "peristaltic" pumps which use flexible tubing to provide the pumping action. Tygon tubing was used throughout the study; however, it was not used more than one week at a time for pumping because the tubing collapses and the pumping accuracy deteriorates significantly. All wastewater pump lines had appropriate connections so that the pump could be disconnected to allow periodic cleaning of the lines.

Air was applied to the bench-scale aeration chambers through a diffuser stone. This air supply was provided by an air compressor and was regulated at flow rates in the range of 3,000 to 7,000 cm^3/min. These high air flow rates were necessary to adequately mix the aeration basin contents and maintain high dissolved oxygen levels in solution in the absence of mixers. The air supply was scrubbed with water to saturate it prior to introducing it into the reactor in order to minimize evaporation. The water scrubbing was preceded by filters that serve to collect oils and other impurities which were present in the air supply.

5.1.2 Monitoring Equipment

5.1.2.1 Zone Settling Velocity Apparatus

The activated sludge settleability was monitored by the zone settling velocity test (Adams et al. 1981). This test consists of observing the settling of the sludge-liquid interface with time. The test was performed with a one-liter graduated cylinder. Experimental observations indicated that

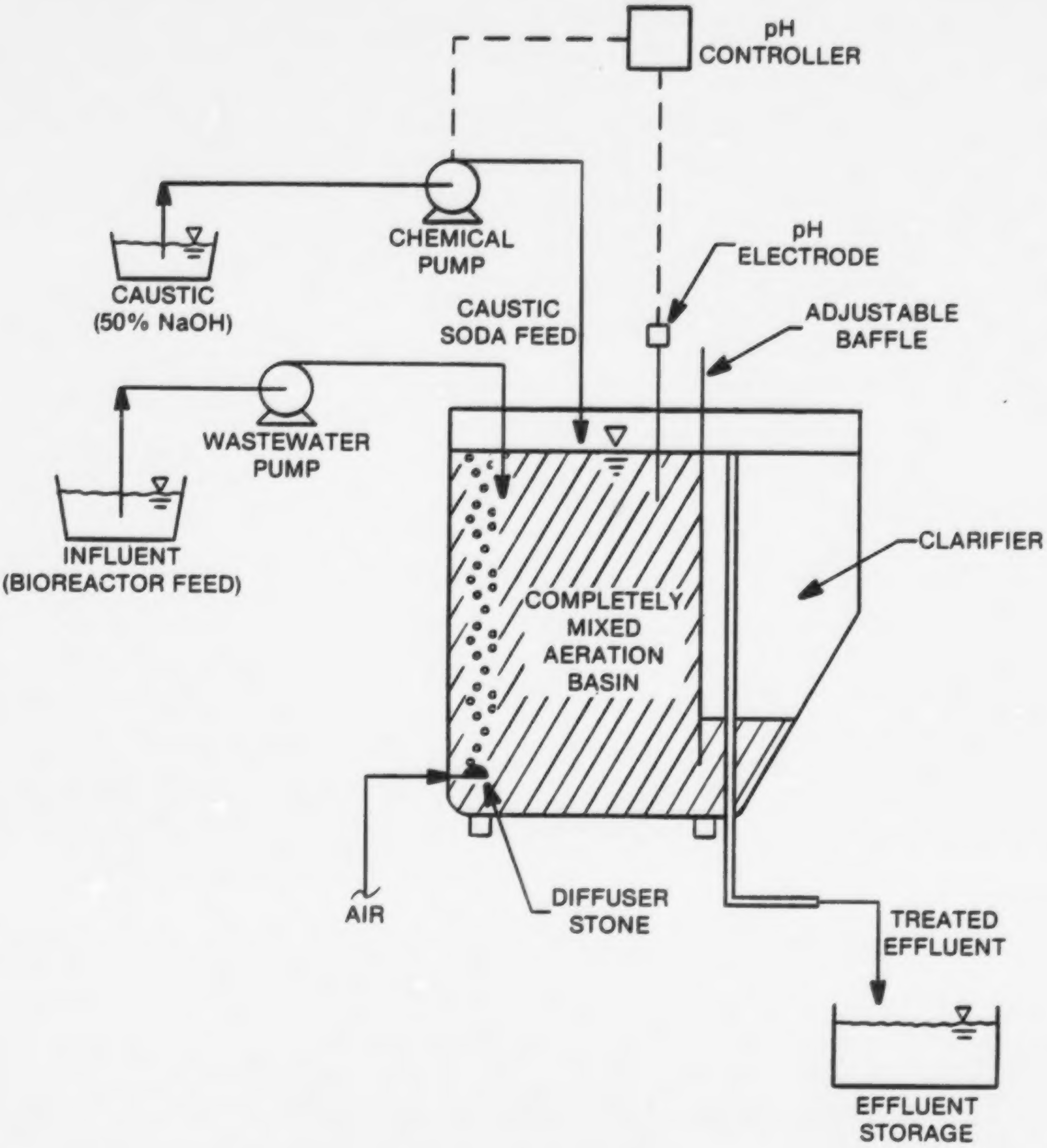

pH
CONTROLLER
CHEMICAL
PUMP
CAUSTIC
(50% NaOH)
pH
ELECTRODE
CAUSTIC
SODA FEED
ADJUSTABLE
BAFFLE
WASTEWATER
PUMP
INFLUENT
(BIOREACTOR FEED)
CLARIFIER
COMPLETELY
MIXED
AERATION
BASIN
AIR
DIFFUSER
STONE
TREATED
EFFLUENT
EFFLUENT
STORAGE

Figure 5-1. Bench-scale activated sludge unit

the suspensions of microbial flocs settled well and it was not necessary to stir the sludge sample during the test.

5.1.2.2 Oxygen Uptake Rate Apparatus

The measurement of microbial oxygen uptake was accomplished by using a dissolved oxygen probe with a stirrer. A galvanic cell oxygen analyzer was used during the study. This device was calibrated by making measurements in wastewater samples that had been analyzed by the azide modification of the Winkler Method for dissolved oxygen analysis.

5.1.2.3 pH Monitoring and Control Apparatus

The measurement and control of pH in the bioreactors was accomplished with pH control equipment developed by the University of Texas for biological treatment testing. The device is similar to pH controllers presently on the market; however, it had the added capability of controlling multiple bioreactors simultaneously to within ± 0.1 of a pH unit (Hulsey 1983).

5.2 DATA REDUCTION AND VALIDATION PROCEDURES

5.2.1 Principal Design Parameters

The principal design parameters for the activated sludge process are substrate utilization, microbial oxygen utilization, and microbial cell yield or sludge production. These parameters are briefly discussed in the following subsections.

5.2.1.1 Substrate Utilization

The rate of substrate utilization can be approximated by the following expression (Lawrence and McCarty 1970):

$$\frac{dF}{dt} = \frac{k_oXS}{K_s+S} \qquad (5\text{-}1)$$

where:

k_o is the maximum utilization coefficient,

K_s is the substrate concentration at which the rate of substrate utilization per unit weight of microorganisms is one-half the maximum,

S is the concentration of substrate in the wastewater,

X is the microbial mass concentration, usually approximated by volatile suspended solids, and

dF/dt is the volumetric rate of microbial assimilation of substrate.

From the above relationship, the specific substrate utilization can be defined as:

$$U = \left(\frac{dF}{dt}\right)/X = \frac{k_oS}{K_s+S} = \frac{Q(S_o-S_e)}{VX} \qquad (5\text{-}2)$$

where:

U is the specific utilization or the rate of substrate removal per unit weight of microorganisms per unit time,

S_o and S_e are the influent and effluent substrate concentrations, respectively,

Q is the hydraulic throughput volume per unit time, and

V is the bioreactor volume.

When insufficient information is available with which to assess the biokinetics associated with the utilization of a specific substrate, a lumped pollutant parameter such as BOD or COD can be used to develop an estimate of the overall treatment performance characteristic of a given activated sludge process. This approach was first proposed by Eckenfelder (Adams et al. 1981) who suggested that the overall pollutant removal velocity was a function of effluent concentration, and that this relationship could be used to establish the residence time in an activated sludge aeration basin. Past studies have consistently indicated that this removal approximates first-order kinetics, specifying a linear relationship between BOD removal velocity and effluent BOD concentration. The following relationship holds for BOD removal in a continuously-fed completely mixed reactor under steady-state conditions:

$$\frac{Q(S_o-S_e)}{VX} = k_1S_e \qquad (5\text{-}3)$$

where:

k_1 is the BOD or COD removal rate coefficient, defined as volume per mass of microorganisms per unit time.

The indicated form of the above equation is conveniently applied when generating the BOD removal rate coefficient from first-order removal kinetics using linear regression techniques to obtain a line of best fit.

In general, the performance of the activated sludge process is related to the BOD loading as defined by the food-to-microorganism ratio (F/M) and the sludge age (θ_c). The BOD loading is defined by the relationship:

$$F/M = (S_o-S_e)/(X\theta) \qquad (5\text{-}4)$$

where:

θ is the hydraulic residence time of the bioreactor.

The right hand side of this equation also expresses the specific substrate utilization rate. The experimentally derived sludge age is defined by:

$$\theta_c = (XV_a)/(\Delta X) \qquad (5\text{-}5)$$

where:

ΔX is the mass (mg) of volatile solids wasted per day from the bioreactor. ΔX is defined as follows:

$$\Delta X = XV_w + VX_e \qquad (5\text{-}6)$$

where:

V_a is the volume of the bioreactor in liters,

V_w is the volume of mixed liquor wasted per day in liters,

V is the volume of effluent collected after 24 hours in liters,

X_e is the effluent volatile suspended solids in mg/L,

F/M is the loading in mg substrate per mg MLVSS per day, and

θ_c is the sludge age in days.

Consistent with the above terminology, the experimental hydraulic residence time is defined as:

$$\theta = V_a/V_i \qquad (5\text{-}7)$$

In this equation, Θ has units of days and V_i is the influent volume in liters.

5.2.1.2 Oxygen Requirements

The oxygen requirements in a biological system are related to the oxygen consumed to supply energy for synthesis and the oxygen consumed for endogenous respiration. This assumes that oxygen must be supplied to the system in order to satisfy the following demands:

- organic carbon and thiocyanate removal,
- endogenous respiration where cells lyse and release soluble oxidizable organic compounds,
- chemical oxidation as measured by the apparent immediate oxygen demand, and
- ammonia which is biologically oxidized to nitrate.

The rate of oxygen utilization is determined from the oxygen uptake analysis. The oxygen utilized is expressed as the respiration rate per mass of mixed liquor volatile solids under aeration. This parameter permits an estimation of the total oxygen utilization during biological treatment. Assuming that a negligible amount of oxygen is required for chemical oxidation, the following expression holds (Adams et al. 1981):

$$R_r/X_a = a'[(S_o - S_e)/(X\Theta)] + b' \qquad (5\text{-}8)$$

where:

R_r is the oxygen utilization per day in mg oxygen/L / day,

a' is the oxygen utilization coefficient for synthesis in mg oxygen/mg substrate removed, and b' is the oxygen utilization for endogenous respiration in mg oxygen/mg VSS / day.

5.2.1.3 Microbial Cell Yield

Microbial cell yield or sludge production is expressed as the synthesis rate per mass of mixed liquor volatile solids under aeration. This parameter permits an estimation of the total sludge production during biological treatment.

Sludge accumulation in the activated sludge system from the biological oxidation of wastewaters can be estimated from the substrate removed. The components of a standard mathematical relationship (Adams et al. 1981) are as follows:

- sludge attributable to nonbiodegradable influent suspended solids,
- sludge produced by cellular synthesis,
- a decrease in sludge due to cellular oxidation by endogenous respiration, and
- a decrease in sludge due to the loss of effluent suspended solids.

The expression for computing excess volatile solids production exclusive of influent solids is:

$$1/\theta_c = Y[(S_o - S_e)/(X\theta)] - b \qquad (5\text{-}9)$$

where:

Y is the growth-yield coefficient, mg VSS/mg substrate; and

b is the endogenous decay coefficient, 1/days.

5.2.1.4 Sludge Settleability

The settling characteristics of the biological sludges were determined in order to design the thickening component of the secondary clarifiers. The following model will be used to describe the relationship between the zone settling velocity of the mixed liquor solids and the initial concentration of the mixed liquor solids (Adams et al. 1981):

$$(ZSV)_i = m \exp(-k_e X_i) \qquad (5\text{-}10)$$

where:

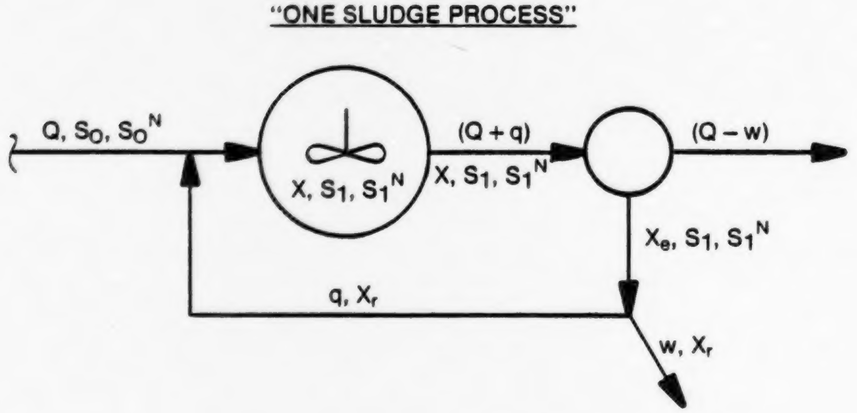
$(ZSV)_i$	is the zone settling velocity of a biological suspension at the initial suspended solids concentration of the suspension in m/hr,
X_i	is the initial suspended solids concentration of the suspension in mg/L, and
m and k_e	are temperature dependent system-specific coefficients.

5.2.1.5 Experimental Process Configuration

The process configuration that was used during the KRW-PDU biooxidation treatability study is the completely mixed reactor, followed in series by gravity settling which allows solids to be recycled. The model for this process, depicted in Figure 5-2, was described by Lawrence and McCarty (1970) and is summarized in Table 5-1.

5.2.2 Experimental Procedures

The accepted experimental procedure for activated sludge treatment is to develop an acclimated seed, operate several systems over a period of several months under stabilized conditions, and closely monitor the response of the systems during the stabilized period of operation.



"ONE SLUDGE PROCESS"

Q, S_O, S_O^N
X, S_1, S_1^N
$(Q + q)$
X, S_1, S_1^N
$(Q - w)$
X_e, S_1, S_1^N
q, X_r
w, X_r

NOTE: The majority of the terms are defined in Table 5-1 of text.

N = ammonia-nitrogen substrate

Q = hydraulic throughput

w = volume of sludge wasted

q = volume of recycle

Figure 5-2. Schematic representation of nitrifying activated sludge process

TABLE 5-1. STEADY-STATE BIOKINETIC MODEL FOR SUSPENDED GROWTH COMPLETELY MIXED RECYCLE REACTORS

Characteristic	Equation[a]
Microbial Growth Rate (μ)	$\mu = (\theta_c)^{-1} = YU - b$
Maximum Microbial Growth Rate (μ)	$\mu = [\theta_c^{m}]\mathrm{lim.}^{-1} = Yk_o - b$
Specific Utilization [$U = (\frac{dF}{dt})/X$]	$U = \frac{k_o S}{K_s + S} = \frac{Q(S_o - S_1)}{(V)(X)}$
Treatment Efficiency (E)	$E = \frac{(S_o - S_1)}{S_o}(10^2)$
Reactor Biomass Concentration (X)	$X = \frac{Y(S_o - S_1)}{1 + b\theta_c} \frac{\theta_c}{\theta}$
Hydraulic Retention Time (θ)	$\theta = \frac{V}{Q} = \theta_c[1 + r - r(X_r/X)]$

[a]

Y = growth yield coefficient, mg/mg.

b = organism maintenance coefficient, day^{-1}.

U = specific utilization, the rate of substrate removal per unit weight of biomass that metabolizes that particular substrate, day^{-1}.

k_o = maximum value of specific utilization that occurs under nonsubstrate limiting growth conditions, day^{-1}.

K_s = half velocity coefficient, which is the value of S when $U = (1/2)k_o$, mg/L.

X = microbial mass concentration, usually approximated by volatile suspended solids, mg/L.

S = substrate or waste constituent concentration, mg/L.

Q = hydraulic throughput, liters/day.

Subscripts:

o = influent.

1 = effluent.

r = sludge recycle stream.

5.2.2.1 Steady-State Testing

The development of design criteria for an activated sludge process consists of collecting data from bioreactors which are operated at different substrate loadings (F/M). Three experimental bioreactors were operated at laboratory room temperature during steady-state testing. The F/M value is usually controlled by varying the detention time. However, the study maintained a set hydraulic detention time of 24 hours for each experimental bioreactor. Consequently, the controlling parameters were the mixed liquor volatile suspended solids concentration under aeration and the sludge age.

Steady-state conditions were assumed once the oxygen uptake rates of the activated sludges had reached consistent levels and the TOC, ammonia, and thiocyanate concentrations of the bioreactor effluent had stabilized.

After the systems had stabilized, the monitoring program emphasized the collection of sufficient data for the development of design parameters. The steady-state testing schedule is presented in Table 5-2. The bioreactors were controlled by sludge age and set quantities of mixed liquor were wasted daily. The quantities were wasted regardless of the concentration of MLVSS under aeration. The study also conducted selected wastewater and treated bioreactor effluent characterization analyses as presented in Table 5-3. The sludges produced during the biooxidation study also were characterized as shown in Table 5-3. The analytical methods and sample handling requirements which were used during the study are presented in Appendix L to this report.

5.2.2.2 Bioreactor Temperature Impact Analysis

It is known that the kinetics of biological oxidation are temperature dependent. Most bacteria have optimum temperatures of activity in the range 25° to 35°C, above which they rapidly die or become inactive. The absolute temperature range for mesophilic microbial reactions is small, usually from 5° to 35°C. The kinetic coefficients of a typical microbial reaction will fit an

TABLE 5-2. BIOREACTOR POST ACCLIMATION SAMPLING AND MONITORING SCHEDULE FOR TREATABILITY STUDY

	Sample Location and Frequency (samples per week)		
Parameter	Influent	Effluent	Aeration Basin
Total Organic Carbon (filtered)	2	2	-
Biochemical Oxygen Demand (filtered)[a,b]	1	1	-
Chemical Oxygen Demand (filtered)[c]	2	2	-
Ammonia-Nitrogen	2	2	-
Nitrite-Nitrogen	2	2	-
Nitrate-Nitrogen	2	2	-
Total Kjeldahl Nitrogen	d	d	-
Thiocyanate	2	2	-
Total Cyanide	2	2	-
Total Phosphorus	1	1	-
Suspended Solids (total and volatile)	3	3	3
Total Dissolved Solids	1	1	-
Alkalinity	1	1	-
pH	7	-	Continuous
Temperature	-	-	7
Flow Rate	-	7	-
Specific Oxygen Uptake Rate	-	-	3
Zone Settling Velocity and Sludge Volume Index	-	-	3

[a] Parameter was used to document treatment performance, not a control parameter.

[b] BOD was analyzed only during the last month of the study. The 20 day BOD analysis was performed on selected samples to determine the nitrogenous oxygen demand.

[c] Parameter was used as a measure of biorefractory oxygen demand.

[d] Analysis conducted infrequently during study.

TABLE 5-3. WASTEWATER CHARACTERIZATION ANALYSES FOR BIOLOGICAL TREATABILITY STUDY

	Sample Location and Frequency (samples per study[a])		
Parameter	Influent Liquor	Effluent Liquor	Bioreactor Sludge
Water Quality Parameters[b]	2	2	-
Extractable Organics (C_8^+ hydrocarbons)	2	2	1
Nonextractable Organics (e.g., organics remaining after analytical extraction such as formates and other organic acids)	2	2	-
Trace Elements[c]	2	2	1

[a] Refers to the steady-state biooxidation testing period only.

[b] pH, conductivity, alkalinity, bicarbonate, carbonate, TOC, COD, phenols, oil and grease, chloride, fluoride, settleable solids, total solids, TSS, TDS, CN^-, SCN^-, TKN, NH_3, $SO_4^=$, $SO_3^=$, $S^=$, TIC.

[c] Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, F, Hg, K, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Se, Si, Ti, Tl, V, Zn.

Arrhenius type of temperature relationship (Adams et al. 1981). The form most often used is as follows:

$$k_2 = k_1 \sigma^{(T_2-T_1)} \qquad (5\text{-}11)$$

where:

k_1 and k_2 are substrate removal rate coefficients at temperatures T_1 and T_2, respectively, day $^{-1}$; and

σ is the temperature correction coefficient.

A bioreactor temperature impact study was conducted during the concluding weeks of the program. This analysis used sludges from a bioreactor that had been operating at an optimum level of performance during steady-state testing. The study was conducted with a continuously-fed bioreactor that was operated at several temperatures below ambient laboratory temperature.

5.2.2.3 Microbial Stress Analysis

As discussed in Section 3 of this document, there are a variety of environmental factors which can inhibit microbial nitrification. The bioreactor steady-state testing program actually addressed several of the most important inhibitory considerations, namely, substrate (NH_3) inhibition, SCN inhibition, pH, and inorganic salt concentration. However, additional stress tests were conducted to assess the impact of non-substrate ions on microbial activity. Non-substrate ions which required additional biological treatability testing were chloride, fluoride, and boron. These pollutants are found at elevated concentrations in most coal gasification wastewaters.

5.2.3 Data Validation

A detailed description of the quality assurance/quality control program used during the biological treatability study is presented in Appendix L to this report. At least 10 percent of all data collected for most analytical parameters were analyzed in duplicate. In addition, replicates, blind standards, and sample spikes also were analyzed throughout the study in order to provide a quality assurance check on analytical procedures. Material balances were performed on the bioreactors to assess the change in nitrogen species throughout the system and overall reactor performance based on hypothesized biochemical transformation.

5.3 MICROBIAL SEED ACCLIMATION

Municipal wastewater activated sludges were used to develop a mixed culture of microbes that were capable of degrading the pollutants in the KRW wastewater. The progress of microbial seed acclimation was assessed using the performance parameters: substrate utilization, oxygen utilization, and microbial cell yield. Normally, microbial cell yield is expressed as the synthesis rate per mass of mixed liquor volatile solids under aeration. However, biosolids were not wasted from the experimental bioreactors during the acclimation period. Consequently, the absolute value of the mixed liquor volatile solids under aeration was used as a measure of relative cell yield.

The rate at which oxygen is utilized in microbial oxidation is intimately related to the growth and maintenance of living microorganisms. Substrates assimilated by microorganisms not only furnish the elements out of which protoplasm is constructed, but also provide the energy for its synthesis. The latter is released through biooxidation. When assimilable substrate is unavailable, the energy required for the maintenance of protoplasm (replacement of worn out components of protoplasm through synthesis) is supplied by an autooxidation commonly called endogenous respiration (Adams et al. 1981). Since both the rate of substrate utilization and the rate of oxygen utilization are associated with growth, these parameters can be used to assess the success of microbial acclimation.

Wastewaters used to acclimate the microbial seed sludge were obtained during a KRW gasifier test burn that used Wyoming sub-bituminous coal. (Actual steady-state testing was conducted with wastewaters produced during a test burn with Pittsburgh #8 bituminous coal.) A characterization of the KRW-PDU wastewaters used during microbial seed acclimation is presented in Table 5-4. The samples were air stripped to reduce the level of sulfides, free cyanide, and ammonia in the KRW wastewater prior to biooxidation testing. Sodium hydroxide (NaOH) was used to elevate the sample pH during the air stripping operation. Ammonia-nitrogen and free cyanide levels in the stripped wastewater samples were less than 300 mg/L and 0.5 mg/L, respectively. There occurred a coincident reduction in sample total alkalinity during the stripping operation.

The addition of NaOH and H_2SO_4 during the pretreatment operations produced a wastewater that was high in total dissolved solids (TDS) as indicated by the data presented in Table 5-4. These TDS levels were thought to be outside the allowable range for successful operation of a biooxidation process. Therefore, the decision was made to dilute the KRW-PDU wastewaters with secondary effluents from a local sewage treatment plant. The operational TDS of the diluted wastewater was maintained between 5,000 and 11,000 mg/L, and the composite samples were spiked with varying amounts of ammonia, thiocyanate, and formate (organic carbon source) during the acclimation study.

A seed sludge obtained from a local sewage treatment plant was used to initiate the acclimation study. The seed sludge was known to contain a low level of nitrifiers, however, the quantity of sulfur oxidizing bacteria present in the seed was unknown. The seed sludge was divided between three test bioreactors each initially operated at hydraulic residence times in excess of four days. KRW wastewaters diluted with secondary effluents from a local sewage treatment plant were fed to three acclimation reactors on a

TABLE 5-4. CHARACTERIZATION OF KRW-PDU WASTEWATERS FOR ACCLIMATION TESTING

	Wastewater Sample Quality[a]	
Parameter	Sample One	Sample Two
pH (pH units)	8.00	8.25
Total Alkalinity as $CaCO_3$, mg/L	2,804	1,299
Total Organic Carbon, mg/L as C	40	40
Chemical Oxygen Demand, mg/L	237	484
Nitrate-nitrogen, mg/L	<0.50	0.50
Nitrite-nitrogen, mg/L	<0.10	<0.10
Ammonia-nitrogen, mg/L	290	274
Organic Nitrogen, mg/L	-[b]	28
Thiocyanate, mg/L	180	130
Total Cyanide, mg/L	-	-
Free Cyanide, mg/L	0.34	0.05
Total Dissolved Solids, mg/L	12,490[c]	49,600[c]
Sodium, mg/L	-	17,000[c]

[a] Wastewaters generated during a test burn with Wyoming Sub-bituminous coal.

[b] Blank means parameter not analyzed.

[c] The samples were pH adjusted with sodium hydroxide and air stripped to reduce the ammonia and acid gases.

continuous basis. The wastewater composite was spiked with ammonia, thiocyanate, formate, and phosphorus. The equilibrium pH of the aeration basin was maintained in the range of pH 6.7 to pH 7.2.

The three acclimation bioreactors operated for approximately 75 days, during which time effluent quality was monitored on a weekly basis. Data for bioreactor effluent quality during the period of microbial seed acclimation are presented in a separate document (Castaldi 1985). During the acclimation test period, the hydraulic residence times in the bioreactors were reduced from four days to 24 hours, and the ammonia and thiocyanate concentrations of the feed wastewater were increased to the design levels (i.e., 250 mg/L ammonia-nitrogen and 150 mg/L SCN).

Sludge yield data typical of the acclimation period are presented in Figure 5-3. The yield data are presented as the absolute magnitude of the mixed liquor volatile suspended solids under aeration for the test bioreactor. These data indicate that the apparent rate of microbial cell production was low and that major growth (i.e., increased cell mass) did not occur until after 40 days of acclimation. Because of this initial low rate of biosynthesis, the decision was made to reseed the test bioreactors after 20 days of operation. The intervening period between the second seeding and the observed increase in microbial cell mass probably was characterized by a shift in the microorganism population from a largely chemoheterotrophic (organic assimilating) community to that of a chemoautotrophic (ammonia, thiocyanate assimilating) community that had the capacity to sustain continuous growth with the inorganic substrates present in the KRW wastewater.

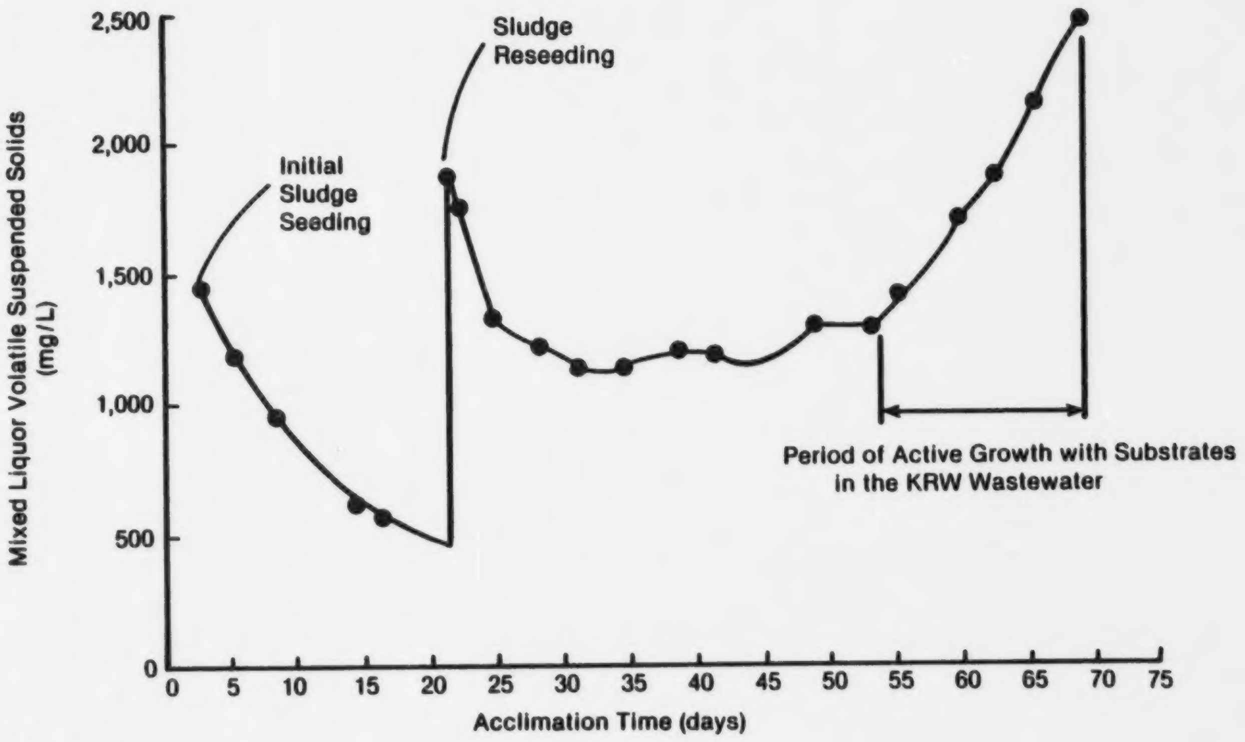


Figure 5-3. Acclimation period sludge yield

SECTION 6

STEADY-STATE EVALUATION AND DETERMINATION OF DESIGN PARAMETERS

This section presents the results of the biological treatability study performed with pretreated KRW-PDU wastewaters described in the previous section. The principal functions of the treatability study were to ascertain the degree of biodegradation possible by conventional activated sludge processes and to develop the basic criteria which would establish proper operation of autotrophic biological treatment facilities.

The necessary coefficients to mathematical models which establish basic operation criteria were determined by operating bench-scale biological reactors of the type described in Section 5 at various substrate loadings and evaluating each system for substrate removal, sludge production, and oxygen requirements. Substrate removal, sludge production, and oxygen utilization in continuously-fed, completely mixed bioreactors were evaluated during this study at water temperatures which varied between 22° and $23.5^{\circ}C$.

Sludge settleability and thickening tests were performed throughout the treatability study in order to determine surface loading rates on secondary clarifiers which would provide both effective clarification and thickening during normal activated sludge process operation.

The sequence of events which defined the biological treatability study of KRW-PDU wastewaters is presented in Table 6-1. The acclimation period was detailed in Section 5. This section addresses the steady-state testing period. The results of the temperature and nonsubstrate ion microbial stress

TABLE 6-1. BIOLOGICAL TREATABILITY PROGRAM MILESTONES

Operation	Period of Study	Description
Acclimation Period	05/16/83 - 07/29/83	Composites were made from KRW-PDU wastewater and secondary effluents; the composites were spiked with ammonia and thiocyanate; acclimation period at design ammonia and thiocyanate levels 06/24/83 - 07/29/83.
Steady-State Period	07/30/83 - 09/23/83	Quasi-steady-state operation using three test bioreactors at design ammonia and thiocyanate levels.
Temperature Study Period	09/24/83 - 11/17/83	Bioreactor #3 was used to evaluate the effects of low temperature operation on treatment performance.
Specific Ion Toxicity Study	10/25/83 - 11/28/83	Bioreactors #1 (control) and #2 used to evaluate the effects of chloride, fluoride, and boron concentration on treatment performance.

studies are presented in Section 7. Chemistry data detailing bioreactor treatment performance during experimental testing are presented in Appendices A and B to this report.

6.1 STEADY-STATE DETERMINATION

In order to model the activated sludge process, the following types of data are required:

- Substrate loadings to the bioreactors and nutrient requirements,
- Oxygen requirements,
- Biological sludge growth rates,
- Hydraulic retention time and mean cell retention time for optimum treatment performance,
- Alkalinity requirements and pH effects,
- Solids settleability,
- Temperature effects, and
- Impacts of toxic or inhibitory substances on sludge growth and substrate removal.

Prior to the evaluation of design parameters from the treatability study data, it is necessary to establish for each reactor the periods of approximate steady-state operation. Even though the steady-state testing period of the bioreactors extended from July 30 to September 23, 1983, periods of bioreactor instability and/or unsatisfactory performance for COD removal occurred in the early portion of this study phase. The unsatisfactory COD removal performance prior to August 1983 may have been due to incomplete SCN biodegradation.

The day-to-day performance and/or operating parameters of percent removal of TOC, COD, NH_3, SCN, and specific oxygen utilization were used as indicators of steady-state operation. Figures 6-1, 6-2, and 6-3 depict the daily record of oxygen utilization, and effluent NH_3-N, COD, and TOC

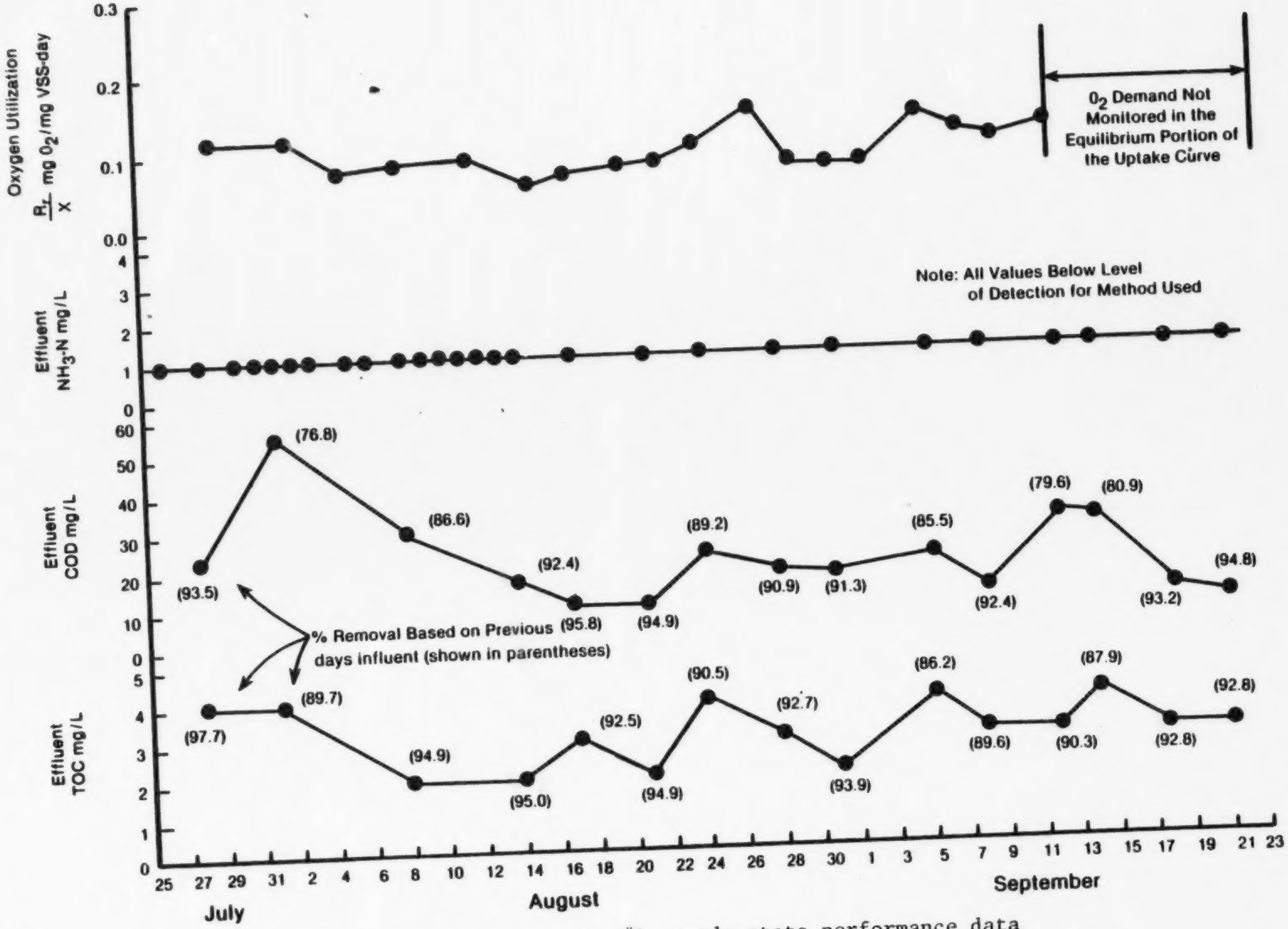


Figure 6-1. Bioreactor #1 steady-state performance data

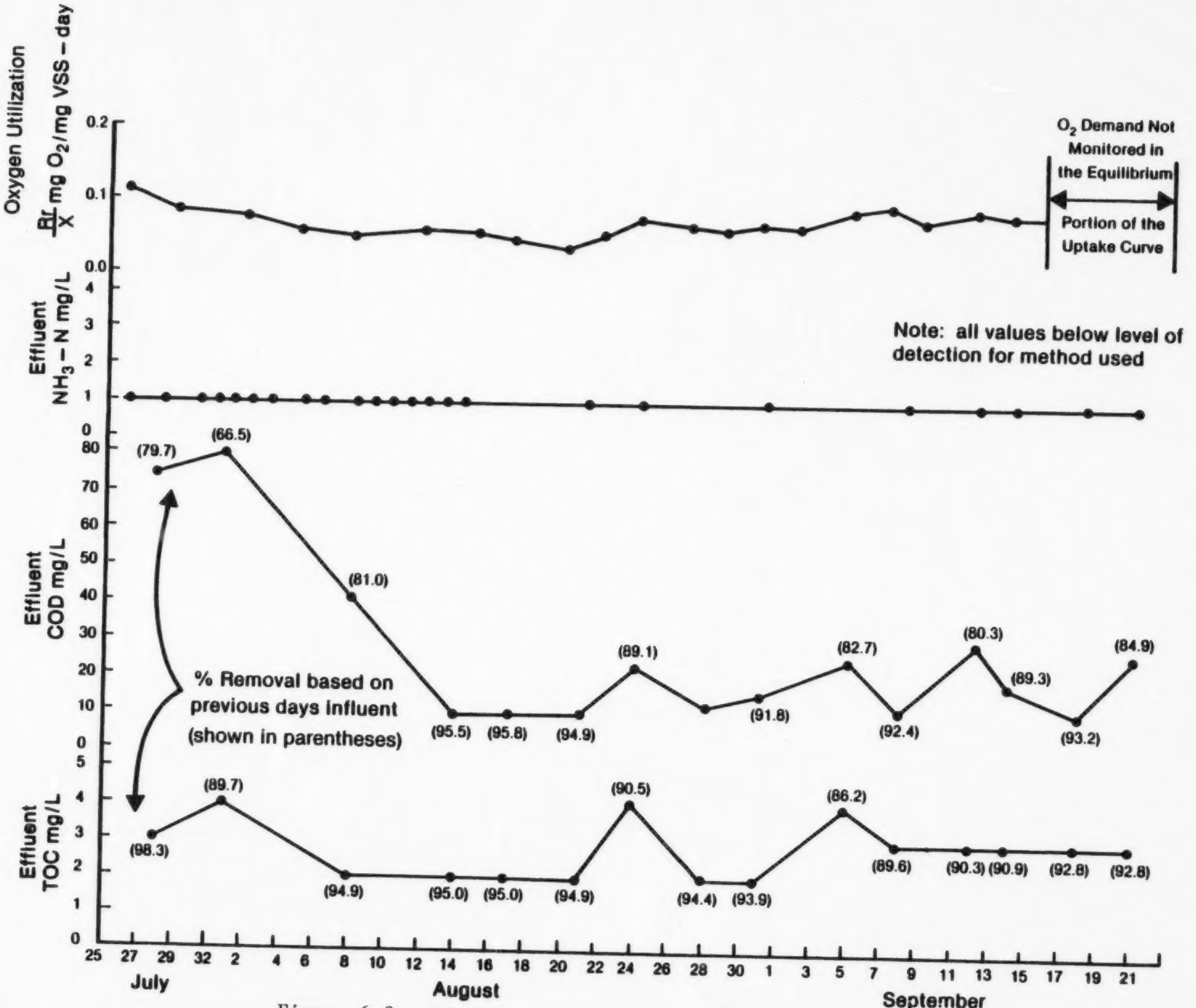


Figure 6-2. Bioreactor #2 steady-state performance data

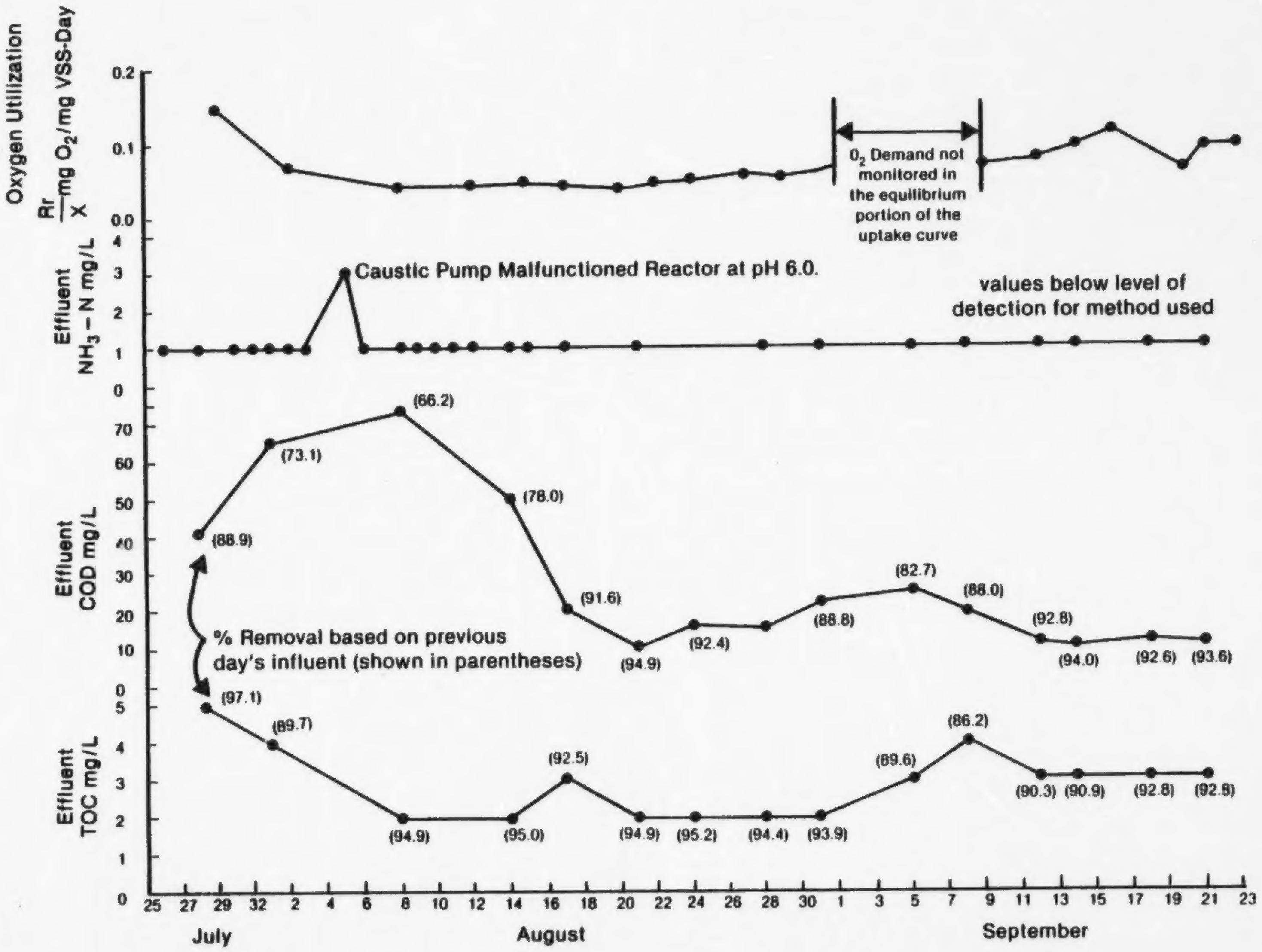


Figure 6-3. Bioreactor #3 steady-state performance data

concentrations for bioreactors 1, 2, and 3, respectively. Table 6-2 presents the corresponding TOC, COD, NH_3-N, and SCN removal information. Coincident, consistent levels of these parameters provided the criterion for establishing which portions of the data record for each reactor should be included in the evaluation. The operating period selected for steady-state analysis was August 13 to September 23, 1983. In the subsequent design parameter evaluation, other analytical data generated during this period for the test bioreactors were presumed to be useful, except for obvious outliers occasionally encountered.

The reasons for the apparent fluctuations in the effluent COD during steady-state testing are unknown. However, certain factors that may have been responsible include fluctuating SCN levels in the influent wastewater and uneven removal of TOC which is dependent on the population dynamics of a completely different microbial culture.

6.2 SUBSTRATE UTILIZATION AND EFFLUENT QUALITY

The mean values and standard deviations of the principal operating parameters examined during the treatability study are presented in Table 6-3. The complete record of bioreactor operating data are included in Appendix D.

Substrate utilization is expressed as the magnitude of the calculated F/M parameter with respect to ammonia, thiocyanate, TOC, COD, and BOD_{20}. Performance evaluation worksheets for ammonia removal are included in Appendix E; COD and SCN removal in Appendix F; and TOC and BOD_{20} removal in Appendix G. The BOD_{20} utilization values were estimated from the experimental data (see Appendix K). It was presumed that influent BOD_{20} concentrations could be correlated to the influent ammonia level and that effluent BOD_{20} concentrations could be correlated to the residual TOC, thereby generating sufficient BOD_{20} data to make a judgment regarding the magnitude of the F/M parameter for this pollutant. The values of 4.08 and 1.87 were used for

TABLE 6-2. POLLUTANT PERCENT REMOVALS DURING STEADY-STATE OPERATION

	Percent TOC Removal			Percent COD Removal			Percent NH_3 Removal[a]			Percent SCN Removal[a]		
Date	Reactor 1	Reactor 2	Reactor 3	Reactor 1	Reactor 2	Reactor 3	Reactor 1	Reactor 2	Reactor 3	Reactor 1	Reactor 2	Reactor 3
08/13	-	-	-	-	-	-	>99	>99	>99	-	-	
08/14	>95.0	>95.0	>95.0	92.4	>95.0	78.0	>99	>99	>99	>99	>99	>99
08/17	92.5	>95.0	92.5	95.8	95.8	91.6	>99	>99	>99	>99	>99	>99
08/21	>94.9	>94.9	>94.9	>94.9	>94.9	94.9	>99	>99	>99	>99	>99	>99
08/24	90.5	90.5	95.2	89.2	89.2	92.5	>99	>99	>99	>99	>99	>99
08/28	91.7	94.4	94.4	91.3	94.2	92.8	>99	>99	>99	>99	>99	>99
08/31	93.9	93.9	93.9	91.3	91.8	88.8	>99	>99	>99	>99	>99	>99
09/05	86.2	86.2	89.7	85.5	82.8	82.8	>99	>99	>99	>99	>99	>99
09/08	89.7	89.7	86.2	91.8	91.8	87.0	>99	>99	>99	>99	>99	>99
09/12	90.3	90.3	90.3	79.6	80.3	92.8	>99	>99	>99	>99	>99	>99
09/14	87.9	90.9	90.9	82.1	89.3	>94.0	>99	>99	>99	>99	>99	>99
09/18	92.9	92.9	92.9	93.2	93.2	92.6	>99	>99	>99	>99	>99	>99
09/21	92.9	92.9	92.9	>94.2	84.9	93.6	>99	>99	>99	>99	>99	>99

[a] All effluent values for ammonia and thiocyanate were less than 1 mg/L of nitrogen and less than 1 mg/L, respectively. These values were taken as 1 mg/L for calculation of percent removal.

TABLE 6-3. BIOREACTOR OPERATING CONDITIONS DURING STEADY-STATE TESTING

Parameter	Bioreactor 1	Bioreactor 2	Bioreactor 3
Substrate Utilization			
Ammonia, $\frac{\text{mg NH}_3\text{-N}}{\text{mg VSS-day}}$	0.149 ± 0.009 (17)[a]	0.107 ± 0.005 (15)	0.084 ± 0.005 (11)
SCN, $\frac{\text{mg SCN}}{\text{mg VSS-day}}$	0.067 ± 0.006 (12)	0.051 ± 0.005 (12)	0.039 ± 0.004 (12)
TOC, $\frac{\text{mg TOC}}{\text{mg VSS-day}}$	0.017 ± 0.003 (12)	0.013 ± 0.002 (12)	0.01 ± 0.002 (12)
COD, $\frac{\text{mg COD}}{\text{mg VSS-day}}$	0.084 ± 0.014 (12)	0.064 ± 0.011 (12)	0.05 ± 0.009 (12)
BOD_{20}[b], $\frac{\text{mg BOD}_{20}}{\text{mg VSS-day}}$	0.619 ± 0.088 (12)	0.45 ± 0.06 (12)	0.35 ± 0.037 (12)
Oxygen Utilization			
Immediate demand, $\frac{\text{mg O}_2}{\text{mg VSS-day}}$	2.92 ± 0.89 (13)	1.79 ± 0.85 (13)	1.87 ± 0.86 (13)
Initial demand, $\frac{\text{mg O}_2}{\text{mg VSS-day}}$	0.40 ± 0.13 (14)	0.27 ± 0.13 (14)	0.24 ± 0.09 (14)
Equilibrium demand, $\frac{\text{mg O}_2}{\text{mg VSS-day}}$	0.14 ± 0.09 (19)	0.08 ± 0.03 (19)	0.08 ± 0.05 (19)
Endogenous demand[c], $\frac{\text{mg O}_2}{\text{mg VSS-day}}$	0.09 ± 0.04 (6)	0.06 ± 0.02 (6)	0.06 ± 0.02 (6)
Sludge age[d], days	58.5 ± 6.0 (19)	104.3 ± 14.5 (19)	150.3 ± 18.7 (19)
MLSS mg/L	2706 ± 180 (18)	3641 ± 169 (18)	4722 ± 113 (18)
MLVSS, mg/L	2128 ± 152 (19)	2937 ± 182 (19)	3772 ± 88 (19)
pH, pH units	7.17 ± 0.16 (45)	7.1 ± 0.24 (47)	7.23 ± 0.05 (43)
Temperature, °C	22.2 ± 0.9 (41)	22.5 ± 0.9 (41)	22.0 ± 0.7 (41)
Alkalinity Usage, mg/day $CaCO_3$	22,132 ± 2228 (12)	21,716 ± 1073 (12)	22,407 ± 2394 (12)
Zone settling velocity, $m^3/m^2/d$	81.6 ± 13.8 (18)	28.9 ± 12.8 (18)	6.2 ± 3.3 (18)
Sludge volume index, mL/gm	83 ± 8 (18)	113 ± 22 (18)	158 ± 13 (18)

[a] Number of data points are presented in parentheses for test period between 13 August and 23 September 1983.

[b] BOD_{20} estimated from $BOD_{20}/NH_3\text{-}N$ ratio and BOD_{20}/TOC ratio for bioreactor influent and effluent samples, respectively (see Appendix K).

[c] Endogenous oxygen demand determined from O_2 uptakes taken after 8 to 10 minutes of aeration without feed.

[d] The hydraulic residence time for each bioreactor is approximately 24 hours.

BOD_{20}/NH_3-N (influent) and BOD_{20}/TOC (effluent), respectively. These correlations are assumed valid for the following reasons:

- More than 75 percent of the influent ultimate biochemical oxygen demand for the KRW wastewater is generated by ammonia-nitrogen oxidation. Therefore, the observed NH_3-N concentration of the wastewater should correlate well with the influent BOD_{20} value.
- The bioreactor effluent is almost completely devoid of ammonia and SCN; therefore, the remaining BOD should be largely comprised of residual organic carbon and this parameter should correlate well with the effluent BOD_{20} value.

The oxygen utilization parameter presented in Table 6-3 was expressed as immediate demand, initial demand, equilibrium demand, and endogenous demand. An explanation of these terms is presented, in part, in Figure 6-4 which depicts typical bioreactor oxygen uptake curves for steady-state operation. In general, the apparent oxygen demand as measured in the first 30 seconds of the oxygen uptake analysis was considerably different than that monitored in the later portion of the test. Normally, the observed magnitude of the oxygen uptake rate is monitored in the first two minutes of the analysis. These values which are defined as the "initial demand" were measured between 15 seconds and two minutes of uptake time. The apparent magnitude of the specific oxygen utilization rate in this portion of the curve was usually one-eighth that of the observed immediate demand. (The calculated values for the observed immediate and initial oxygen demands are presented in Appendix C to this report.) When the specific oxygen utilization was determined in the portion of the uptake curve below the two minute mark, a third magnitude of this parameter was obtained. This portion of the curve was defined as the "equilibrium demand" and probably represents a substrate limiting environment. When the oxygen uptake analysis was performed after 10 minutes of bioreactor aeration without the introduction of feed, the observed specific oxygen utilization value was presumed to be characteristic of the endogenous demand. These data are also presented in Appendix C.

Figure 6-5 shows the daily record of the initial demand parameter for all of the test bioreactors. This form of the oxygen utilization parameter is

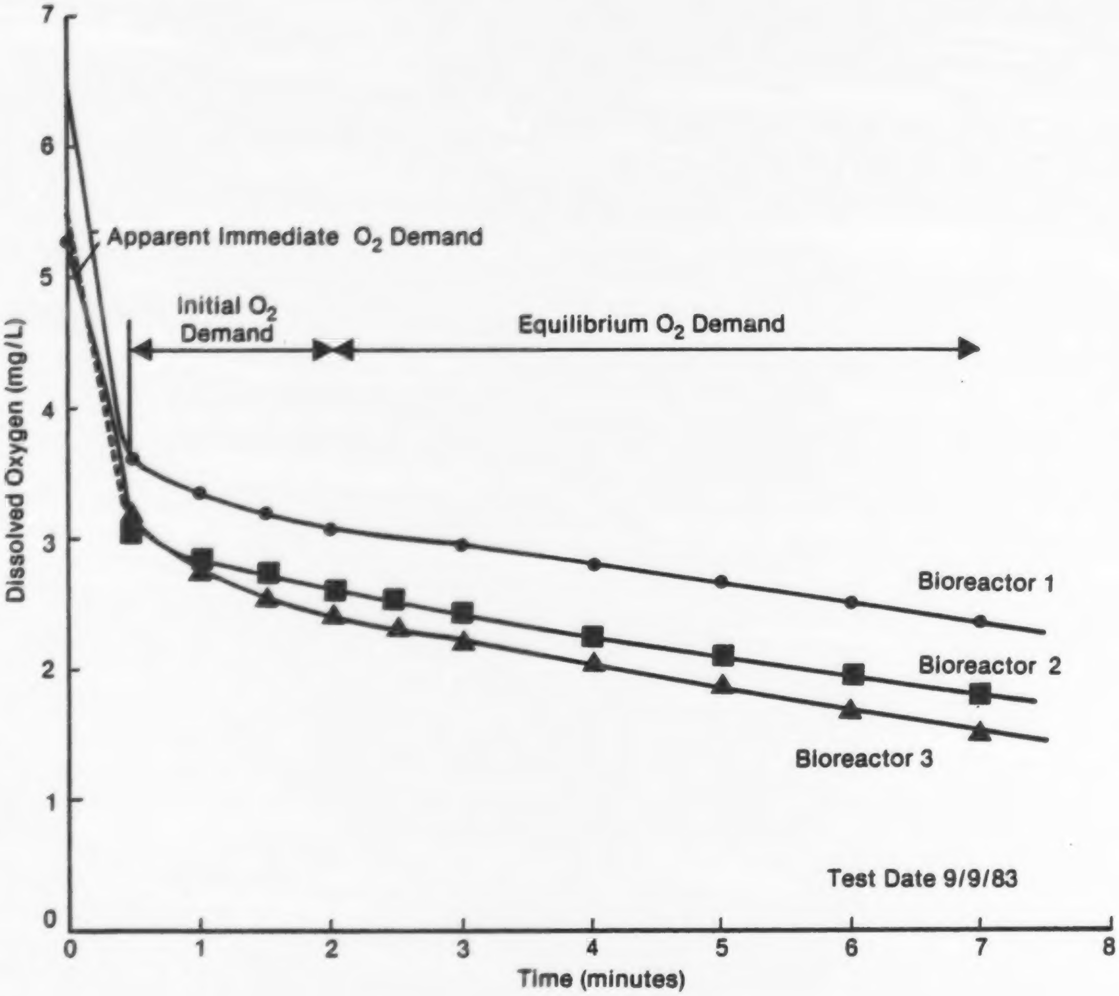


Figure 6-4. Typical bioreactor oxygen uptake curves during steady-state operation

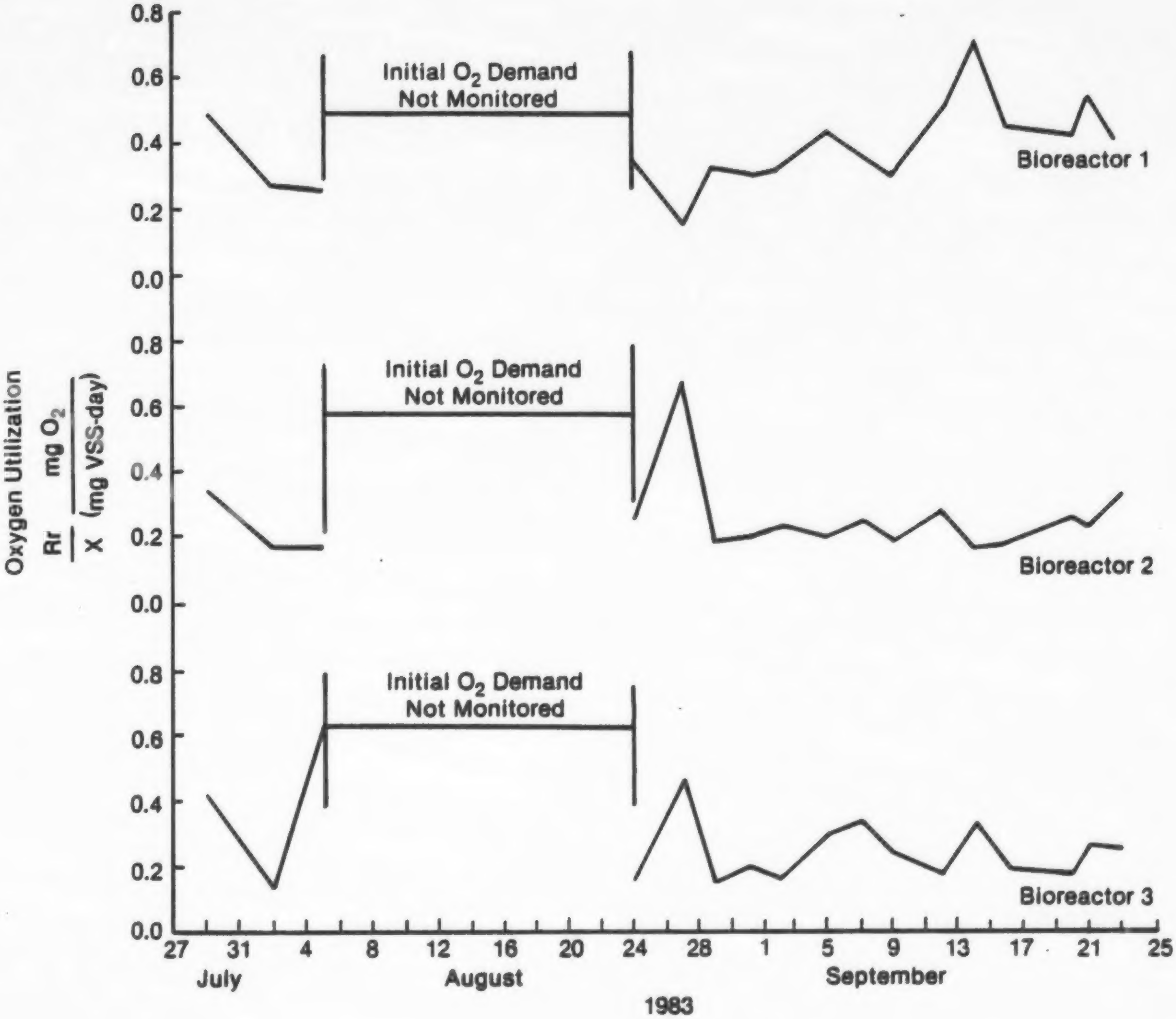


Figure 6-5. Steady-state initial oxygen demand

more variable than the equilibrium demand parameter that was used to assess steady-state performance. It is apparent from these data that the observed specific oxygen utilization rates for the KRW wastewater, as measured in a substrate-rich environment, can vary considerably; and this condition must be incorporated into the development of the oxygen requirement design parameter.

This analysis indicates that the design parameters that present the most practicable assessment of bioreactor oxygen utilization are the immediate and initial oxygen demand values because neither the equilibrium nor the endogenous demand occur in a substrate-rich environment. However, the apparent variability associated with both the immediate and initial oxygen demand values is substantial, and this variability seems not to be predicted by the observed pollutant levels in the bioreactor since effluent quality was usually quite consistent throughout the study. It is surmised that most of the variability in the oxygen demand may be due to the sensitivity of the nitrifier population to changing wastewater characteristics.

The effluent qualities of the three test bioreactors are indicated by the statistical data presented in Table 6-4. The steady-state period was generally characterized by excellent pollutant removal, with comparable effluent values observed for all three bioreactors with respect to ammonia, thiocyanate, TOC, COD, and BOD_{20}. Additional characterization analyses also were performed on the effluents from bioreactor 3 on two separate occasions, and these data are presented in Tables 6-5, 6-6, and 6-7 for conventional pollutants, trace elements, and extractable/chromatographable organics identified by GC-MS analysis, respectively.

As an indicator of treatment effectiveness, the values presented in these tables can be considered relative to the feedwater (bioreactor influent) characterization data presented in Section 4 of this report. In general, all of the microbial substrate-specific pollutants were at reduced levels in the effluent after treatment.

TABLE 6-4. STEADY-STATE BIOREACTOR EFFLUENT QUALITY

Parameter	Bioreactor #1[a]			Bioreactor #2[a]			Bioreactor #3[a]		
	Mean	Standard Deviation	N[b]	Mean	Standard Deviation	N[b]	Mean	Standard Deviation	N[b]
BOD_{20}[c], mg/L	5.6	1.4	12	5.1	1.4	12	5.0	1.2	12
TOC, mg/L	3.0	0.7	12	2.8	0.8	12	2.7	0.7	12
COD, mg/L	17	7.6	12	17	7.3	12	18	10.9	12
NH_3-N, mg/L	<1	-[d]	13	<1	-	13	<1	-	13
NO_3-N, mg/L	286	13.2	12	286	10	12	286	10.2	12
NO_2-N, mg/L	0.13[e]	0.07	12	0.12[e]	0.07	12	<0.1	-	12
SCN, mg/L	<1	-	12	<1	-	12	<1	-	12
Total CN, mg/L	0.89	0.08	12	0.90	0.11	12	0.86	0.17	12
TDS, mg/L	2,929	64	12	3,002	161	12	2,976	75	12
TSS, mg/L	12	6.4	18	12.3	6.2	18	12.4	5.7	18
VSS, mg/L	7	3.2	18	7.5	3.3	18	8	3	18
Alkalinity ($CaCO_3$), mg/L	32	10.8	12	29	11.7	12	36	6.9	12
pH, pH units	7.17	0.16	45	7.1	0.24	47	7.23	0.05	43
Total P, mg/L	2.8	1.7	6	2.8	1.6	6	2.8	1.6	6

[a] Operating temperature between 22° and 23.5°C.

[b] Number of observations.

[c] Estimated from BOD_{20}/TOC ratio (see Appendix K).

[d] Blanks mean parameter not analyzed.

[e] Mean not a true value because numerous values were reported <0.1 mg/L.

TABLE 6-5. BIOREACTOR TREATED EFFLUENT CHARACTERIZATION

Component[a]	Treated Effluent[b]	
	Sample 1	Sample 2
pH (pH units)	6.98	7.60
Conductivity (μ mhos/cm at 25°C)	3,950	3,870
Carbonate alkalinity as $CaCO_3$	0	0
Bicarbonate alkalinity as $CaCO_3$	37	42
Total solids	2,900	2,830
Total dissolved solids	2,960	2,830
Total suspended solids	13	6
Total settleable solids (mL/L)	<0.1	<0.1
Chloride	499	418
Cyanide	0.83	1.17
Fluoride	17	21
TKN	<1	3
Ammonia as N	<5	<5
Thiocyanate	<1	<1
Sulfide as S	<1	<1
Sulfite as SO_3	16	<1
Sulfate as SO_4	299	330
Phenol	<0.01	<0.005
TOC	3	1
TIC	4	7
COD	<10	<10
Oil and Grease	<1	<1

[a] All results as mg/L except as noted in parentheses beside the component.

[b] Sample One collected 9/5/83 and Sample Two collected 9/22/83 during steady-state operation.

TABLE 6-6. TRACE ELEMENTS PRESENT IN BIOTREATED WASTEWATERS AND SLUDGES

	Treated Effluent[a] (mg/L)		Biosludge[b] (μg/g)	
Constituent	Sample 1	Sample 2	Total	Dissolved
Silver	<0.002	0.007	<0.002	<0.002
Aluminum	0.43	0.20	560	52
Arsenic	<0.06	<0.06	<0.06	<0.06
Boron	9.7	12	14	4
Barium	0.27	0.084	39	28
Beryllium	<0.0005	0.001	0.065	0.015
Calcium	-	-	380	370
Cadmium	<0.002	0.009	1.2	0.56
Cobalt	<0.006	0.010	<0.056	<0.06
Chromium	0.002	0.002	5.3[c]	5.3
Copper	<0.001	0.018	10	10
Iron	0.45	0.54	120	110
Mercury	<0.03	<0.03	<0.03	<0.03
Potassium	6.6	7.1	57	50
Magnesium	6.0	6.1	46	41
Manganese	<0.001	0.006	7.1	7.0
Molybdenum	<0.002	0.015	<0.019	<0.02
Sodium	890	840	59	50
Nickel	<0.003	<0.003	3.4	1.3
Phosphorus	3.6	2.4	560	180
Lead	<0.084	<0.08	2.3	1.1
Sulfur	-	-	290	200
Antimony	<0.032	<0.032	<0.030	<0.030
Selenium	<0.08	<0.08	<0.8	<0.8
Silicon	9.8	13	110	100
Titanium	<0.005	0.10	3.0	3.0
Thallium	<0.091	<0.091	<0.85	<0.8
Vanadium	<0.003	0.057	<0.028	<0.03
Zinc	<0.028	0.12	49	41

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[a] Sample 1 collected 9/5/83 and Sample 2 collected 9/22/83.

[b] Sample obtained at the conclusion of the steady-state analysis.

[c] Hexavalent chromium 0.15 μg/g.

TABLE 6-7. GC-MS RESULTS FOR BIOTREATED WASTEWATERS AND SLUDGES

Compound	Treated Effluent (ppb)	Biosludge (μg/g)
1,1,2-trichloroethane	-[a]	0.93
Perchloroethylene	-	0.18
Octanoic acid, methyl ester	-	0.61
1,1,2,2-tetrachloroethane	-	2.5
Pentachloroethane	-	0.27
Benzoic acid	-	0.38
Benzeneacetic acid	-	1.0
2-methylthiobenzothiazole	0.4	0.42
Dodecanoic acid	-	3.0
$C_{14}H_{28}O_2$ acid	-	6.9
N-methylpyrole	2.8	-
Naphthalene	0.2	-
Benzothiazole	3.3	-
4-Methoxycycloheptanone	ND[b]	-
Biphenyl ether	0.4	-
Carbazole	0.5	-
Hexadecanoic acid	ND	-
Alkylbenzenesulfonamide	26	-

[a] Blank indicates compound not detected.

[b] ND indicates compound not detected in effluent but was present in the untreated wastewater.

For comparison purposes, a plot of the observed progress of the biochemical oxygen demands of the effluents from the steady-state test bioreactors are presented in Figure 6-6. These data depict a normal BOD curve for the oxidation of residual organic material. The influence of nitrification is not apparent (no nitrogenous demand) which supports the analytical data regarding effluent ammonia-nitrogen levels.

Total Kjeldahl nitrogen (TKN) was not analyzed regularly during steady-state operation because most of the nitrogen in the KRW wastewater existed as ammonia. However, the parameter organic nitrogen was measured after ammonia removal during the early stages of the treatability study. This analysis was also discontinued during steady-state testing because of relatively consistent influent concentrations of approximately 30 mg/L and virtually negligible effluent concentrations.

Trace elements data for Bioreactor 3 indicate that there is little apparent difference between the influent and effluent quality associated with biooxidation treatment because the majority of the trace elements are present at low concentrations. Sodium is present in the bioreactor effluent at elevated concentrations because of the addition of sodium hydroxide (NaOH) to the test reactors for pH control during biooxidation. However, accumulation of some pollutants in the biosludges is apparent from the trace element data also present in Table 6-6. Elements that are at elevated concentrations in the sludge (relative to the water phase) are aluminum, barium, calcium, iron, potassium, magnesium, phosphorus, silicon, and zinc. Elements that were also bioaccumulated, but to lower levels are cadmium, chromium, copper, manganese, nickel, lead, and titanium. The presence of high concentrations of iron, copper, and nickel in the biosludge may indicate a potential for the accumulation of complexed cyanides in the sludge. This may present a possible constraint on the handling of wastewater treatment sludge from a commercial-scale treatment facility.

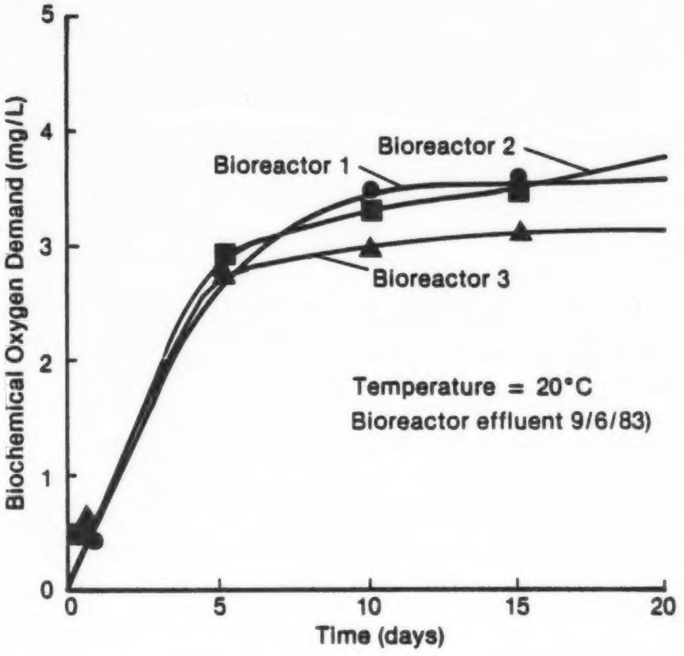

Figure 6-6. Treated effluent biochemical oxygen demand

These pollutants are at elevated concentrations in the biosludges because of the long operational sludge ages of the autotrophic activated sludge process. (Bioreactor 3 maintained a sludge age of 150 days during the study.) Long bioreactor sludge ages promote the accumulation of certain pollutants in the waste activated sludges. There is an apparent trade-off between the system stability needed to guarantee year-round nitrification that results from long sludge age operation, and the potential effects of bioaccumulation which could require that the waste sludges be handled as a hazardous material. However, sludge produced from a long cell residence time autotrophic (activated sludge) system will be a small quantity on any given day. Therefore, these sludges are more likely to be wasted from the process seasonally, depending on mixed liquor requirements during either winter or summer operation.

The GC-MS results for biotreated wastewaters and sludges were presented in Table 6-7. When these data are compared to the influent wastewater characteristics presented in Section 4 they indicate little apparent reduction during biooxidation of the low levels of extractable/chromatographable organics found in the KRW wastewater. The data relative to biosludge characteristics are inconclusive because a new group of compounds were found in the sludges that had not been detected in the wastewater. This is due, in part, to bacteria cell chemistry since the assortment of organic acids identified may be characteristic of metabolic intermediates generated during the biodegradation of the organic compounds in the wastewaters. However, the presence of such compounds as 1,1,2-trichloroethane, 1,1,2,2-tetrachloroethane, and pentachloroethane cannot be explained from the data base. It is concluded that more data are required before the extractable/chromatographable organics contained in the autotrophic biosludges can be accurately assessed. At present, the data seem to indicate that bioaccumulation of organics in the activated sludges is not a concern.

6.3 MATERIAL BALANCES

Evidence of the active population of nitrifying bacteria that characterized the mixed culture of microorganisms used in the treatability study can be obtained from material balances of the nitrogen series and the associated alkalinity usage. A biooxidation nitrogen balance is presented in Table 6-8 for Bioreactor 1. The influent ammonia-nitrogen concentrations were adjusted to reflect the presence of that portion of the thiocyanate in the wastewater which is converted to ammonia during biooxidation. This conversion is reflected in the measured NO_3-N concentration in the treated effluents after biooxidation. From these data it can be seen that the microbial population was effective in the utilization of available nitrogen forms. In general, the bioreactor mass balances closed within plus or minus 8 percent of the available nitrogen (exclusive of a finite level of organic nitrogen which may also have been present). This would indicate that a small portion of the available nitrogen probably went to microbial cell synthesis. Another factor that might account for lower nitrogen levels in the effluent is ammonia stripping to the atmosphere during aeration. However, this is presumed to be a minor consideration because equilibrium NH_3-N concentrations in the bioreactor were always less than 1 mg/L, and the pH of the wastewater was in a range where the nonionized component was small (i.e., < 5 percent of the total nitrogen in the mixed liquor). Higher nitrogen levels in the effluent than the influent may be due to either cell lyse or the presence of organic nitrogen in the wastewater that was not accounted for by the analysis. Both of these conditions could increase the influent NH_3-N concentration to where it would effect effluent quality.

Similar data are presented for Bioreactors 2 and 3 in Tables 6-9 and 6-10, respectively. These data conform to the results of the aforementioned evaluation.

TABLE 6-8. BIOREACTOR 1 NITROGEN BALANCE[a]

	Nitrogen In				Nitrogen Out				
Date	NH_3 Adjusted for SCN	NO_2[b]	NO_3	Total	NH_3[c]	NO_2[b]	NO_3	Total	Change in Total Nitrogen Attributable To Uptake by Biomass
08-14	297	<0.10	0.8	298	<1	<0.10	293	293	+ 5
08-17	288	<0.10	1.0	289	<1	0.16	280	280	+ 9
08-21	285	<0.10	0.7	286	<1	<0.10	283	283	+ 3
08-24	286	0.21	0.54	287	<1	0.30	275	276	+ 1
08-28	284	0.21	0.47	284	<1	<0.10	308	308	- 24
08-31	280	0.11	0.54	281	<1	<0.10	290	290	- 9
09-05	297[d]	<0.10	2.0	299	<1	<0.10	293	293	+ 6
09-08	266	<0.10	3.4	270	<1	<0.10	258	258	+ 12
09-12	287	0.16	2.8	290	<1	<0.10	303	303	- 13
09-14	286	0.12	1.7	288	<1	0.23	278	278	+ 10
09-18	281	<0.10	0.7	281	<1	<0.10	283	283	- 2
09-21	278	<0.10	0.5	279	<1	<0.10	283	283	- 4

[a] All values as mg/L.

[b] A value of 0.10 mg/L was used for concentrations of <0.10 mg/L NO_2-N.

[c] A value of 0.15 mg/L was used for concentrations of <1 mg/L NH_3-N.

[d] Average of two measurements.

TABLE 6-9 BIOREACTOR 2 NITROGEN BALANCE[a]

	Nitrogen In				Nitrogen Out				
Date	NH_3 Adjusted for SCN	NO_2[b]	NO_3	Total	NH_3[c]	NO_2[b]	NO_3	Total	Change in Total Nitrogen Attributable To Uptake by Biomass
08-14	297	<0.10	0.8	298	<1	0.34	286	287	+ 11
08-17	288	<0.10	1.0	289	<1	<0.10	287	287	+ 2
08-21	285	<0.10	0.7	286	<1	<0.10	284	284	+ 2
08-24	286	0.21	0.54	287	<1	<0.10	290	290	- 3
08-28	284	0.21	0.47	284	<1	<0.10	305	305	- 21
08-31	280	0.11	0.54	281	<1	<0.10	295	295	- 14
09-05	297[d]	<0.10	2.0	299	<1	<0.10	290	290	+ 9
09-08	266	<0.10	3.4	270	<1	<0.10	273	273	- 3
09-12	287	0.16	2.8	290	<1	<0.10	296	296	- 6
09-14	286	0.12	1.7	288	<1	<0.10	278	278	+ 10
09-18	281	<0.10	0.7	281	<1	<0.10	273	273	+ 8
09-21	278	<0.10	0.5	279	<1	<0.10	275	275	+ 4

[a] All values as mg/L.

[b] A value of 0.10 mg/L was used for concentrations of <0.10 mg/L NO_2-N.

[c] A value of 0.15 mg/L was used for concentrations of <1 mg/L NH_3-N.

[d] Average of two measurements.

TABLE 6-10. BIOREACTOR 3 NITROGEN BALANCE[a]

	Nitrogen In				Nitrogen Out				
Date	NH_3 Adjusted for SCN	NO_2[b]	NO_3	Total	NH_3[c]	NO_2[b]	NO_3	Total	Change in Total Nitrogen Attributable To Uptake by Biomass
08-14	297	<0.10	0.8	298	<1	<0.10	287	287	+ 11
08-17	288	<0.10	1.0	289	<1	<0.10	283	283	+ 6
08-21	285	<0.10	0.7	286	<1	<0.10	283	283	+ 3
08-24	286	0.21	0.54	287	<1	<0.10	300	300	- 13
08-28	284	0.21	0.47	284	<1	<0.10	305	305	- 21
08-31	280	0.11	0.54	281	<1	<0.10	285	285	- 4
09-05	297[d]	<0.10	2.0	299	<1	<0.10	283	283	+ 16
09-08	266	<0.10	3.4	270	<1	<0.10	267	267	+ 3
09-12	287	0.16	2.8	290	<1	<0.10	295	295	- 5
09-14	286	0.12	1.7	287	<1	<0.10	275	275	+ 12
09-18	281	<0.10	0.7	281	<1	<0.10	285	285	- 4
09-21	278	<0.10	0.5	279	<1	<0.10	288	288	- 9

[a] All values as mg/L.

[b] A value of 0.10 mg/L was used for concentrations of <0.10 mg/L NO_2-N.

[c] A value of 0.15 mg/L was used for concentrations of <1 mg/L NH_3-N.

[d] Average of two measurements.

Alkalinity usage material balances are presented for the three test bioreactors in Tables 6-11 through 6-13. The balances for the theoretical alkalinity demand are based on the following algorithm:

$$\mathrm{Alk}_{destroyed} - (\mathrm{Alk}_{IN} - \mathrm{Alk}_{OUT}) = \mathrm{Alk}_{THEO} \qquad (6\text{-}1)$$

where:

$\mathrm{Alk}_{destroyed}$	is the theoretical alkalinity usage based on the nitrification reaction,
Alk_{IN}	is the alkalinity measured in the influent to the bioreactor,
Alk_{OUT}	is the alkalinity measured in the effluent, and
Alk_{THEO}	is the calculated theoretical alkalinity usage.

The actual alkalinity usage is an experimentally determined value based on the quantity of sodium hydroxide added to the bioreactors during biooxidation treatment.

The material balances for the associated (actual) alkalinity usage indicate good agreement with the theoretical demand based on the nitrification reaction. In general, the observed alkalinity usage was slightly greater than the calculated theoretical usage which is indicative of the alkalinity destruction associated with the biodegradation of organic carbon and thiocyanate. The actual alkalinity demands were experimentally determined to be 7.74, 7.59, and 7.82 mg $CaCO_3$ per mg NH_3-N utilized for Bioreactors 1, 2, and 3, respectively.

Bioreactor phosphorus uptake is presented in Table 6-14. Phosphate salts (KH_2PO_4) were added to the feedwater to satisfy the supplemental nutrient requirements of the microbial population for cell synthesis. The apparent

TABLE 6-11. BIOREACTOR 1 ALKALINITY MATERIAL BALANCE[a]

Date	In	Out	Destroyed by Nitrification	Theoretical Usage	Actual Usage
08-14	1,016	313	23,687	22,984	24,978
08-17	1,130	441	22,105	21,416	18,139
08-21	1,057	529	21,938	21,409	22,029
08-24	2,124	556	22,708	21,140	22,343
08-28	1,149	235	24,228	23,314	20,914
08-31	743	205	21,523	20,984	22,813
09-05	1,481	212	23,614	22,345	22,094
09-08	1,095	236	20,398	19,539	20,934
09-12	540	364	22,628	22,451	27,001
09-14	832	318	22,370	21,855	21,765
09-18	493	364	21,465	21,336	22,254
09-21	509	411	21,485	21,387	20,322

[a] All values as mg $CaCO_3$/day.

TABLE 6-12. BIOREACTOR 2 ALKALINITY MATERIAL BALANCE[a]

Date	In	Out	Destroyed by Nitrification	Theoretical Usage	Actual Usage
08-14	1,012	367	23,585	22,940	22,895
08-17	1,127	451	22,047	21,371	21,851
08-21	1,057	561	21,938	21,442	21,771
08-24	2,147	528	22,955	21,336	23,219
08-28	1,157	337	24,390	23,570	20,819
08-31	756	252	21,910	21,406	21,529
09-05	1,527	241	24,354	23,068	22,111
09-08	1,126	298	20,970	20,142	19,028
09-12	538	263	22,515	22,240	22,174
09-14	828	207	22,268	21,646	21,121
09-18	502	196	21,839	21,533	21,980
09-21	517	198	21,820	21,501	22,094

[a] All values as mg $CaCO_3$/day.

TABLE 6-13. BIOREACTOR 3 ALKALINITY MATERIAL BALANCE[a]

Date	In	Out	Destroyed by Nitrification	Theoretical Usage	Actual Usage
08-14	1,038	399	24,203	23,564	24,914
08-17	1,172	480	22,922	22,230	24,367
08-21	1,061	509	22,021	21,469	22,052
08-24	2,200	495	23,520	21,816	21,630
08-28	1,166	340	24,592	23,766	18,326
08-31	770	268	22,298	21,796	23,852
09-05	1,537	312	24,507	23,282	22,950
09-08	1,131	432	21,065	20,367	18,249
09-12	544	422	22,763	22,641	26,122
09-14	828	403	22,268	21,842	22,925
09-18	497	411	21,652	21,566	21,062
09-21	520	409	21,947	21,837	22,436

[a] All values as mg $CaCO_3$/day.

TABLE 6-14. BIOREACTOR PHOSPHORUS UPTAKE[a]

	Bioreactor 1			Bioreactor 2			Bioreactor 3		
Date	Phosphorus In	Phosphorus Out	Attributable to Uptake by Biomass	Phosphorus In	Phosphorus Out	Attributable to Uptake by Biomass	Phosphorus In	Phosphorus Out	Attributable to Uptake by Biomass
08-14	6.0	6.0	0	6.0	5.8	0.2	6.0	5.8	0.2
08-21	5.6	3.0	2.6	5.6	3.0	2.6	5.6	3.0	2.6
08-28	2.5	1.6	0.9	2.5	2.6	0.9	2.5	1.6	0.9
08-31	5.8	2.0	3.8	5.8	2.0	3.8	5.8	2.0	3.8
09-08	5.6	2.3	3.3	5.6	2.3	3.3	5.6	2.3	3.3
09-18	4.2	1.8	2.4	-	-	-	4.2	1.8	2.4
09-21	-	-	-	4.2	1.9	2.3	-	-	-

[a] All values as mg/L.

phosphorus needs were met by the addition of phosphorus to the feedwater at a mass rate of approximately 0.2 percent of the BOD_{20} removal.

Biosludge analysis indicated a sizable uptake of phosphorus by the autotrophic activated sludges. This luxury uptake may be beyond the actual amount of phosphorus required for cell synthesis. However, the accumulated phosphorus is also subject to release from the sludges in an anaerobic environment which poses an additional consideration in solids handling design; namely, the appropriate treatment of decant liquors from sludge thickening and/or digestion facilities. This may present an added advantage in that phosphorus can be recycled within the biotreatment system thereby reducing the demand for this supplemental nutrient.

6.4 DESIGN PARAMETER DETERMINATION

Experimental data fitted to the design formulations presented in Section 5 provide the basis for this analysis. The experimentally determined coefficients for sludge production, oxygen utilization, and substrate removal are presented in Table 6-15. Summary data used to develop these formulations are presented in Appendices E through G. In general, the experimental data fit the design correlations well with correlation coefficients (r) of greater than 0.99 in most cases. The graphical form of the sludge production formulation is shown in Figures 6-7 and 6-8 for ammonia and biochemical oxygen demand, respectively. The growth-yield coefficient was derived by applying linear regression analysis to data relating to mass of volatile solids wasted during the study to the substrate utilization characteristics of the three test bioreactors. Of particular note is the similarity of the value of the endogenous decay coefficient for each of the substrates examined (i.e., 0.006 and 0.007 day^{-1} for ammonia and BOD_{20}, respectively). This would suggest that the different sludge production data sets support one another.

It is apparent that the sludge yield for the autotrophic activated sludge process is quite small. Typical values of the sludge yield coefficient

TABLE 6-15. SUMMARY OF DESIGN PARAMETERS

	Observed Coefficients		
	Y	b	
Parameter	mg VSS/mg Substrate	day^{-1}	r
SLUDGE PRODUCTION			
Ammonia-nitrogen	0.155	0.006	0.998
Thiocyanate	0.361	0.008	0.99
Total organic carbon	1.446	0.008	0.99
Chemical oxygen demand	0.298	0.008	0.992
Biochemical oxygen demand[a]	0.038	0.007	0.997

	a'	b'	
Parameter	mg O_2/mg Substrate	mg O_2/mg VSS/day	r
OXYGEN UTILIZATION			
Ammonia-nitrogen			
Immediate demand	18.564	0.081	0.984
Initial demand (mean value)	2.203	0.055	0.993
Initial demand (maximum value)[b]	3.655	0.126	0.997
Biochemical oxygen demand[a]			
Initial demand (mean value)	0.528	0.055	0.992
Initial demand (maximum value)[b]	0.739	0.131	0.999

	Eckenfelder Model	Lawrence-McCarty Model
	k_1[c]	k_o[d]
Parameter	L/mg VSS/day	mg Substrate/mg VSS/day
SUBSTRATE UTILIZATION KINETICS		
Biochemical oxygen demand[a]	0.09	—
Ammonia-nitrogen (mean value)	—	0.118[e]
Ammonia-nitrogen (maximum value)[b]	—	0.19
Thiocyanate (mean value)	—	0.052[f]
Thiocyanate (maximum value)	—	0.083

[a] 20 day BOD.

[b] 99% confidence limit of the true mean value.

[c] First-order removal rate coefficient.

[d] Maximum specific substrate removal coefficient (zero order).

[e] SD = ± 0.028 mg NH_3-N/mg VSS/day (N=43).

[f] SD = ± 0.012 mg SCN/mg VSS/day (N=36).

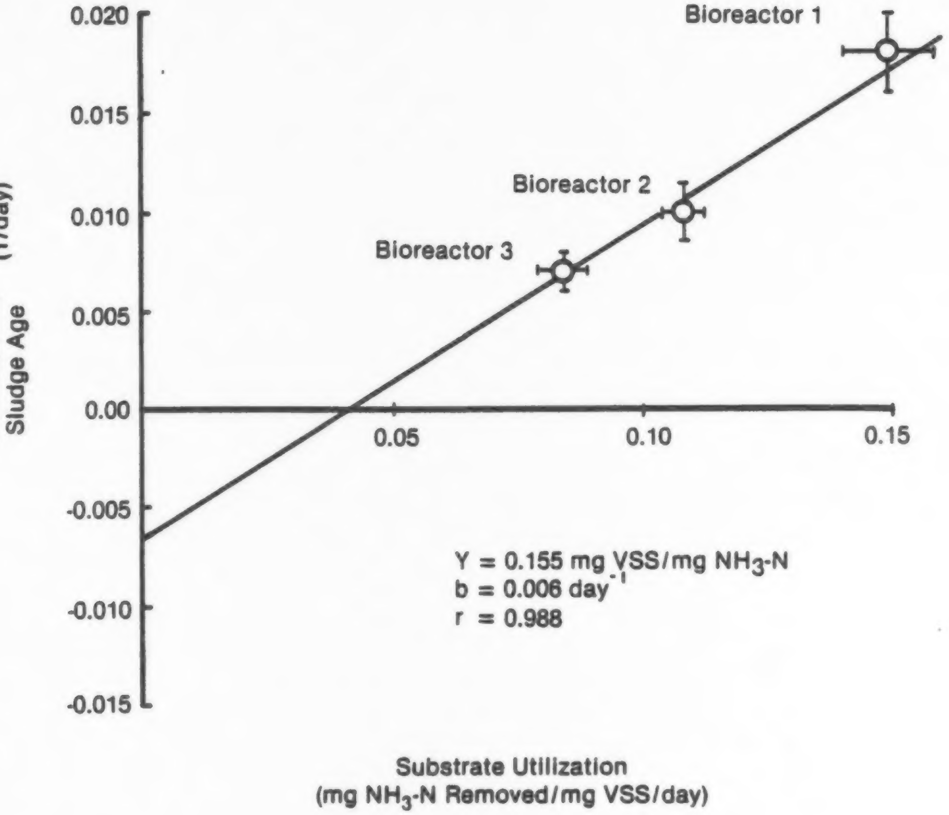

Figure 6-7. Sludge production based on ammonia removal

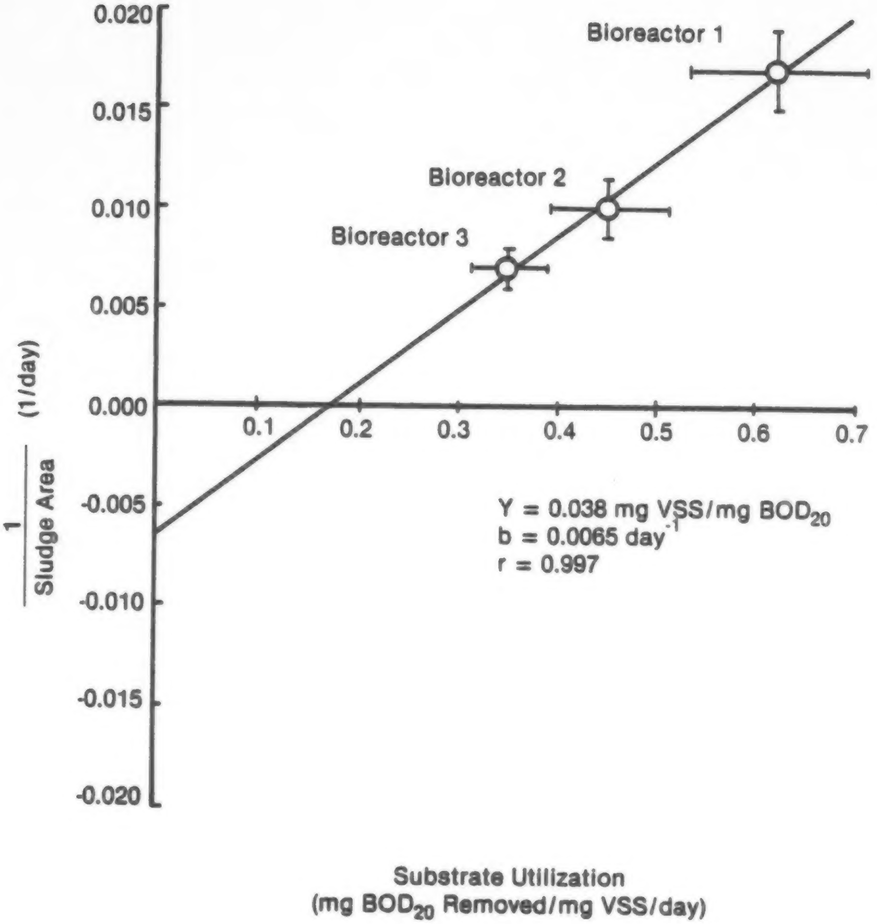

Figure 6-8. Sludge production based on BOD_{20} removal

for carbonaceous substrate removal vary between 0.4 and 0.9 mg VSS per mg substrate (BOD) utilized (Eckenfelder 1966). Test data for the KRW wastewater produced a BOD-based sludge yield value that is an order of magnitude smaller than a heterotrophic process.

The low sludge yield of a chemoautotrophic process is a major factor in process design because it specifies an operational system that does not require a large capital investment for sludge handling facilities. This type of biological treatment process should permit a seasonal sludge wastage schedule that would depend on mixed liquor population dynamics. Periods of cold weather that specify a slower microbial metabolism will require that sludge not be wasted in order to increase the active mixed liquor solids concentration to meet normal pollutant loadings. Sludge wastage rates during warm weather operation are dependent on pollutant loading and normal operation kinetic factors. Under certain conditions the normal loss of biological solids with decanted liquors from the process clarifier might balance microbial yield, thus requiring no special sludge wastage during normal operation.

The graphical form of the oxygen utilization formulation is shown in Figure 6-9 for NH_3-N removal. The function was developed with the initial oxygen demand data. Coefficients for a similar formulation developed with the immediate oxygen demand data are presented in Table 6-15. Both of these functions express relative magnitudes for the oxygen utilization coefficients associated with the treatment of KRW wastewaters. However, the initial demand formulation would underestimate the theoretical oxygen requirement for ammonia removal by a factor of two while the immediate demand formulation would overestimate this requirement by a factor of four. It is apparent that neither of these formulations offer a useful interpretation of the oxygen requirements for biooxidation of the KRW wastewater during steady-state operation. (It should be emphasized, however, that the immediate oxygen demand formulation may be more characteristic of a stress condition rather than steady-state operation which would specify an oxygen transfer requirement which accounts for periods of bioreactor upset and/or substrate overload.)

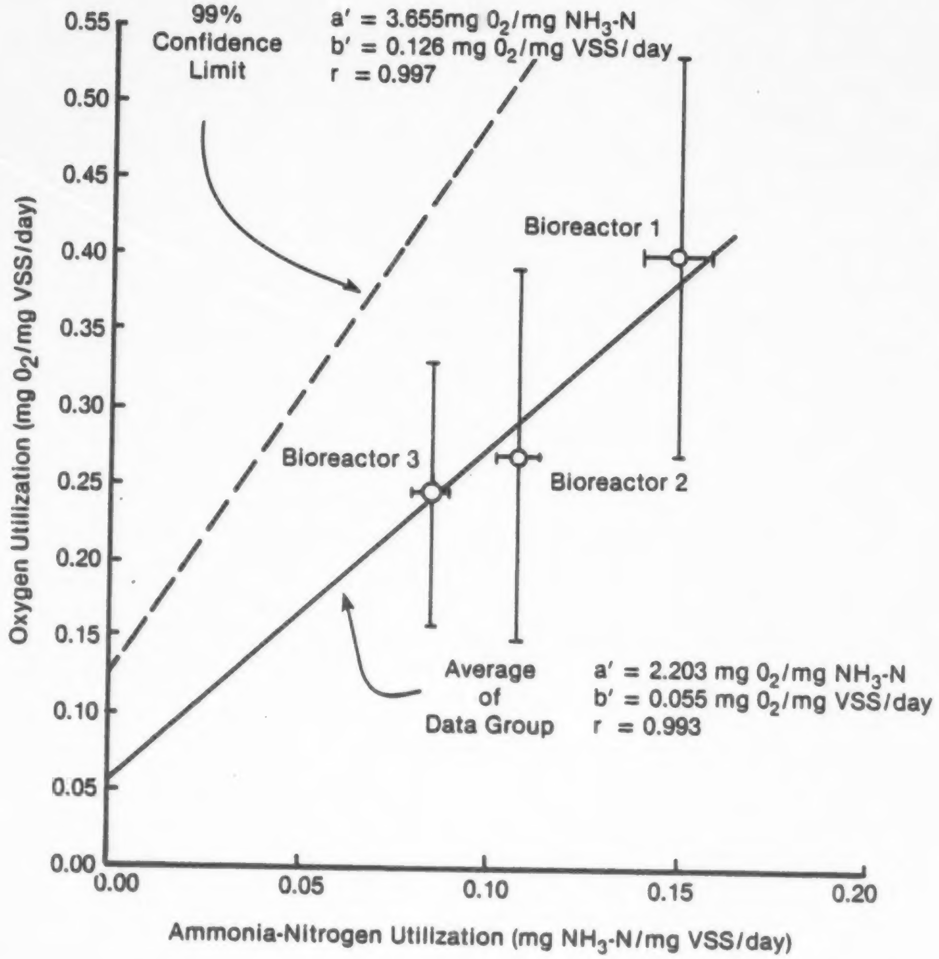

Figure 6-9. Oxygen utilization based on ammonia removal

A graphical representation of oxygen utilization as a function of the BOD_{20} utilization is shown in Figure 6-10. This function was developed from initial oxygen demand data. Of particular note is the similarity of the value of the endogenous respiration coefficient estimated from both the NH_3-N removal and the BOD_{20} utilization data (b' = 0.055 mg O_2/mg VSS/day). The formulation based on BOD_{20} utilization more closely meets the theoretical oxygen requirements if the 99 percent (upper) confidence limit of the data set is used to generate the oxygen utilization coefficients. The observed values of the BOD_{20}-based oxygen utilization coefficients for the KRW-PDU wastewater also are summarized in Table 6-15.

A graphical presentation of substrate utilization in terms of BOD_{20} removal kinetics for the KRW wastewater is shown in Figure 6-11. This function was derived by applying a best fit analysis with zero-intercept to the steady-state effluent qualities associated with Bioreactors 1 through 3. The observed BOD_{20} first-order rate constant is 0.09 L/mg VSS/day.

Substrate utilization kinetics for both ammonia and thiocyanate removal were evaluated using the Lawrence-McCarty Model. Substrate utilization data applied to this model are presented in Appendix H to this report. In general, the data indicate that the observed kinetic function is zero order (i.e., $K_s << S$). Therefore, it was then possible to calculate a maximum specific substrate removal coefficient, k_o, for both ammonia and thiocyanate from the combined substrate utilization data sets of the three test bioreactors. These values also are presented in Table 6-15.

The operational sludge ages of the test bioreactors varied between 58 and 150 days and the apparent activated sludge settling quality as measured by the zone settling velocity showed a deterioration at higher sludge ages. Typical bioreactor sludge settling curves during steady-state operation are presented in Figure 6-12. The initial portions of the sludge settling curves for both Bioreactors 2 and 3 obviously depict particle-liquid interface, hindered settling.

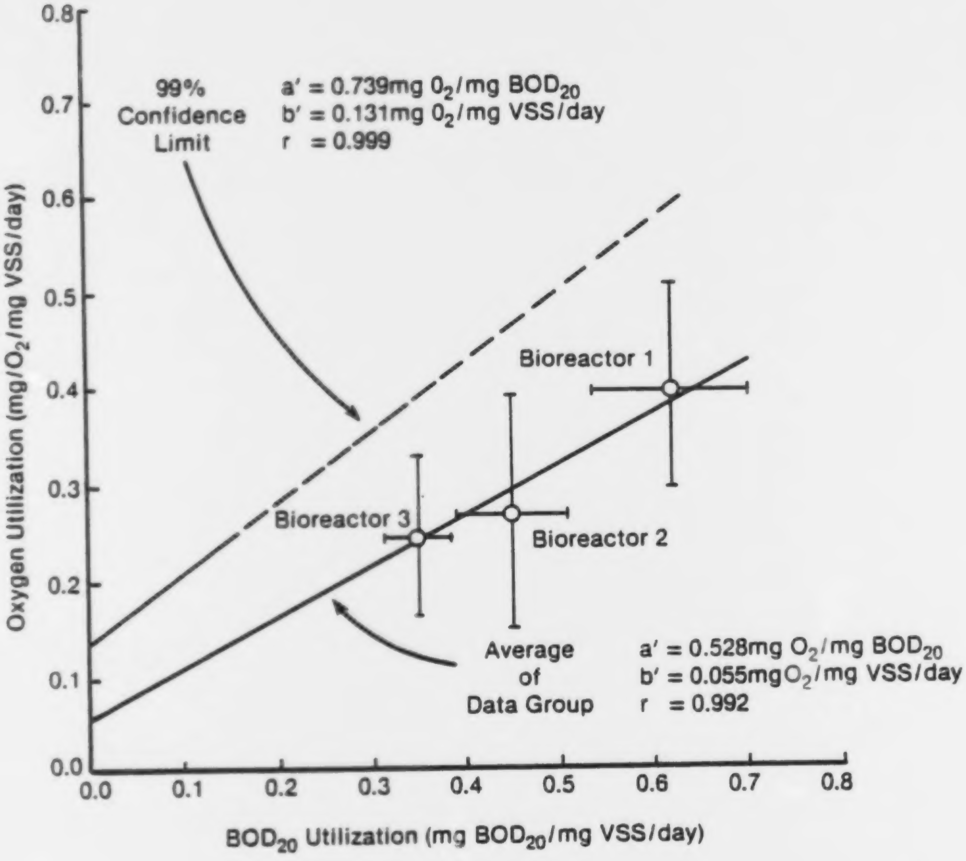

Figure 6-10. Oxygen utilization based on BOD$_{20}$ removal

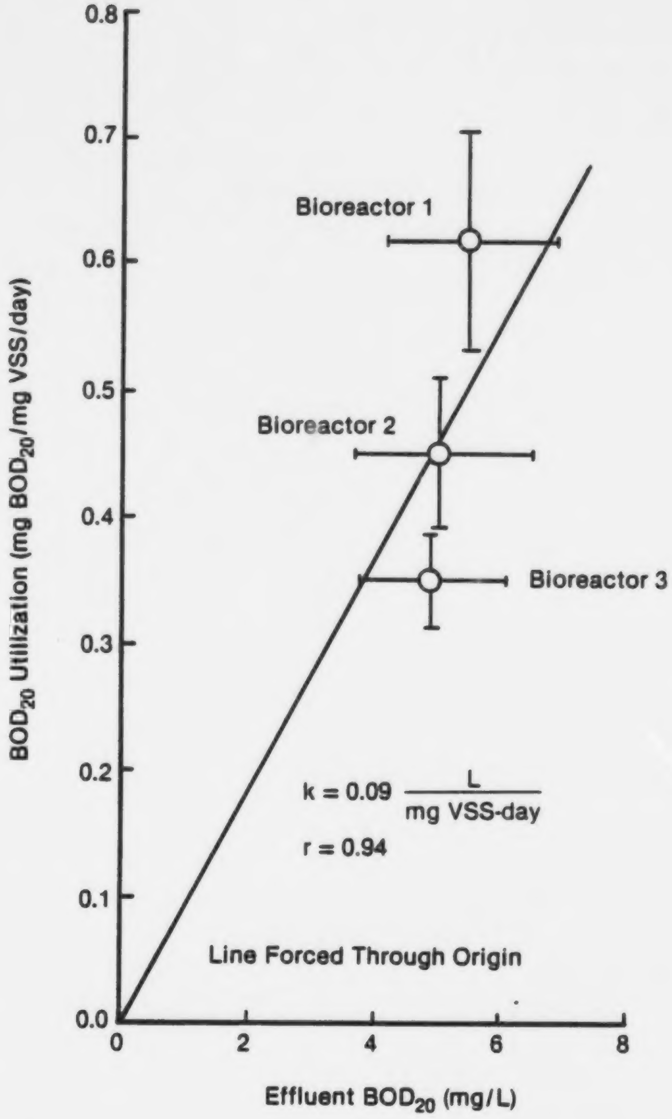

Figure 6-11. Substrate utilization based on BOD removal

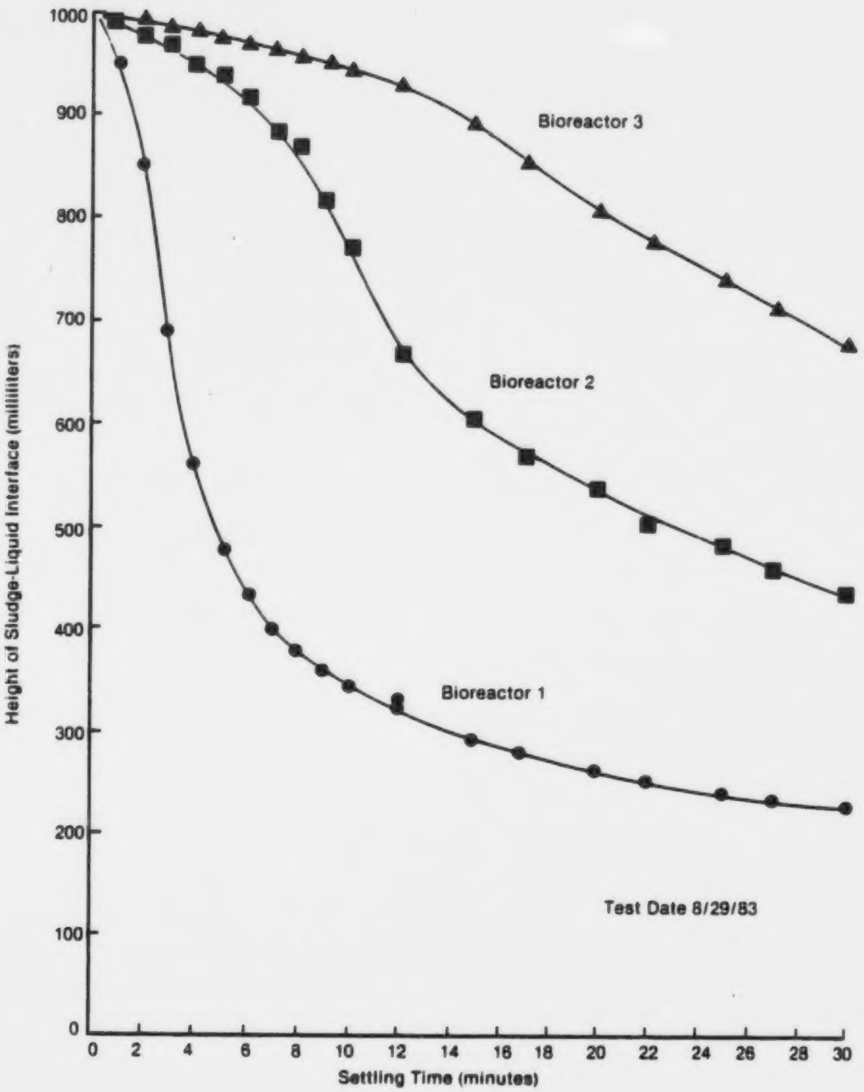

Figure 6-12. Typical steady-state sludge settling curves

The average value of the sludge volume index (SVI) observed during the study varied between 83 and 158 mL/gm suspended solids. An SVI of greater than 150 generally indicates poorly settling sludge. The value of the index that is characteristic of a good settling sludge will vary with the mixed liquor solids concentration. In general, these data indicate that the poorest settleabilities occurred in the highest sludge age reactor.

The experimental relationship between the zone settling velocity of the mixed liquor solids and the initial concentration of the mixed liquor is depicted in Figure 6-13. The equation which describes this function is:

$$ZSV_i = 128\ e^{-0.00131X_i} \qquad (6\text{-}2)$$

the terms of which were defined in Section 5.

This relationship demonstrates the degree to which mixed liquor concentration impacts upon sludge settleability. The apparent deterioration in sludge settleability is quite pronounced for a relatively narrow range of mixed liquor concentrations. This is not usually true of activated sludges developed from the biodegradation of carbonaceous BOD substrates. However, poor settleability is not uncommon of activated sludges that contain a large population of nitrifiers. This effect may also be a function of sludge age as was previously noted.

Although the zone settling velocity was low at high mixed liquor concentrations, this condition did not represent one of a bulking sludge. Moreover, the sludge thickening capacity of the mixed liquor solids was excellent throughout the study. This indicates that the design of the secondary treatment clarification unit operation can be accomplished without chemical aids and within hydraulic and solids loading rates common of most industrial activated sludge processes.

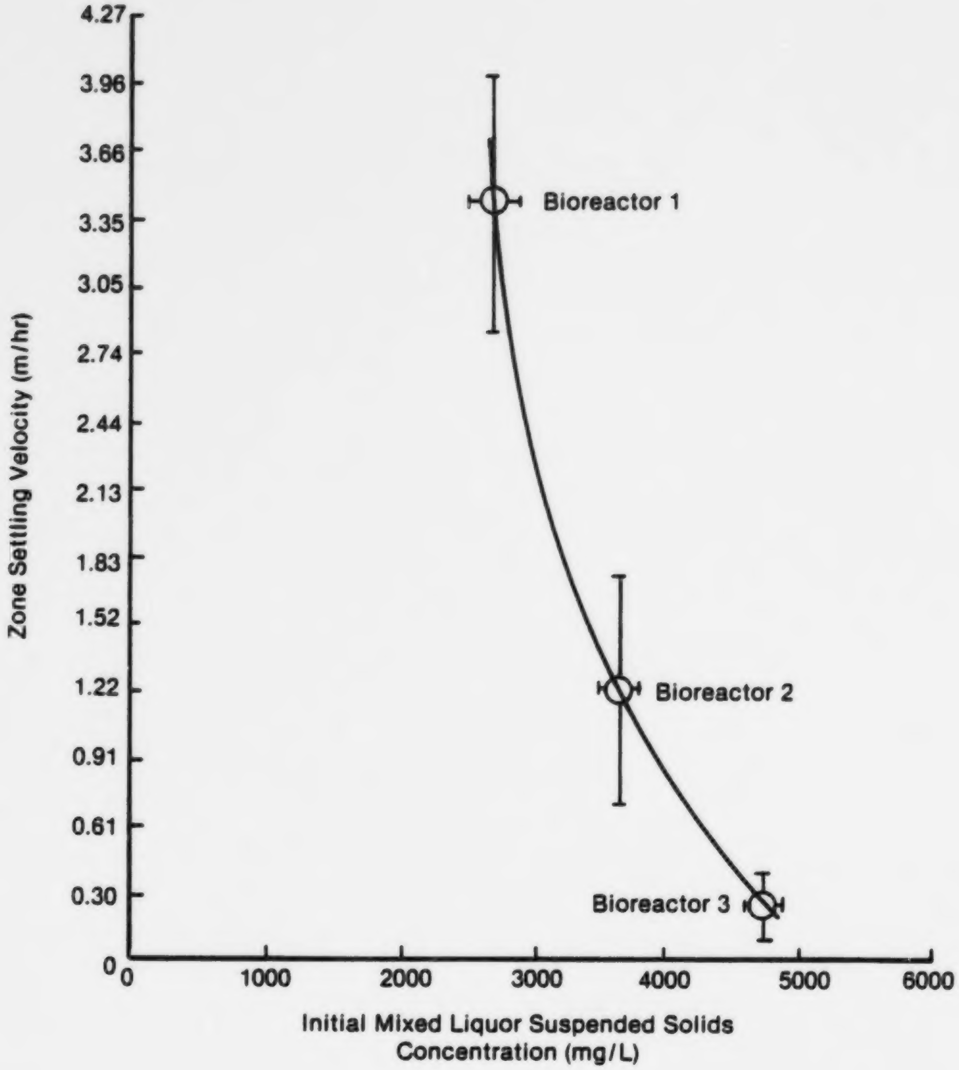

Figure 6-13. Sludge settling velocity as a function of mixed liquor concentration

SECTION 7

MICROBIAL STRESS STUDIES

Microbial stress studies with activated sludges developed during steady-state treatability testing of the KRW wastewater were the following:

- A temperature impact evaluation to identify the effects of temperature changes on ammonia-nitrogen and thiocyanate biodegradation.
- A nonsubstrate ion toxicity evaluation to document the impacts of increased concentrations of chloride, fluoride, and boron on biological treatment efficiency.

The primary objective of this phase of the biological treatability study was to investigate wastewater characteristics typical of fluid- and entrained-bed gasifiers that might suppress nitrification in the activated sludge process. Because the pronounced effects of temperature on nitrification rates are widely recognized, and operating experience has shown that it is commonly difficult to maintain nitrification during cold weather, the initial phase of the microbial stress study investigated the effects of temperature on nitrification.

7.1 TEMPERATURE STUDY

A series of tests were performed with a continuously-fed, completely-mixed bioreactor to identify the effects of operation at lower ambient temperatures on bioreactor substrate removal performance. These tests were conducted at equilibrium bioreactor temperatures of 22°C to 5.6°C. Bioreactor operating conditions during the temperature study are presented in Table 7-1.

TABLE 7-1. BIOREACTOR OPERATION DURING TEMPERATURE STUDY[a]

Parameter	22.0 ± 0.7°C	17.9 ± 0.2°C	14.9 ± 0.2°C	11.5 ± 0.7°C	9.4 ± 0.4°C	8.0 ± 0.3°C	5.6 ± 1.2°C
Substrate Utilization							
Ammonia, $\frac{\text{mg } NH_3\text{-N}}{\text{mg VSS-day}}$	0.084 ± 0.005 (11)[b]	0.086 ± 0.004 (6)	0.085 ± 0.004 (3)	0.082 ± 0.001 (4)	0.024 ± 0.027 (6)	0.010	0.008
Thiocyanate, $\frac{\text{mg SCN}}{\text{mg VSS-day}}$	0.039 ± 0.004 (12)	0.04 ± 0.003 (6)	0.036 ± 0.002 (3)	0.035 ± 0.001 (4)	0.037 ± 0.001 (6)	0.044	0.044 ± 0.008 (5)
Sludge age, days	150 ± 19 (19)	150 ± 21 (6)	154 ± 7 (3)	113 ± 16 (4)	107 ± 11 (6)	113 ± 9 (2)	116 ± 23 (5)
MLSS, mg/L	4,722 ± 113 (18)	4,544 ± 130 (6)	4,580 ± 26 (3)	4,623 ± 95 (4)	4,560 ± 62 (6)	4,370 ± 85 (2)	4,243 ± 32 (5)
MLVSS, mg/L	3,722 ± 88 (19)	3,568 ± 87 (6)	3,600 ± 20 (3)	3,630 ± 36 (4)	3,496 ± 97 (6)	2,745 ± 106 (2)	2,693 ± 218 (5)
Sludge volume index, mL/gm	158 ± 13 (18)	170 ± 12 (6)	161 ± 7 (3)	133 ± 20 (4)	128 ± 19 (6)	86 ± 2 (2)	82 ± 3 (5)
Total dissolved solids, mg/L	2,976 ± 75 (12)	2,782 ± 64 (6)	3,055 ± 52 (3)	2,796 ± 171 (4)	707 ± 301 (6)	505 ± 21 (2)	488 ± 31 (5)
pH, pH units	7.23 ± 0.05 (43)	7.08 ± 0.21 (12)	7.03 ± 0.03 (7)	7.03 ± 0.07 (8)	7.09 ± 0.12 (14)	7.09 ± 0.01 (6)	7.14 ± 0.11 (8)

[a] Data are shown as the mean ± one standard deviation from the mean for period between 24 September and 17 November 1983.

[b] Number of observations are presented in parentheses.

Test data at each temperature were developed with a single bioreactor that had been acclimated to the KRW wastewater during steady-state testing at a mixed liquor temperature of 22°C. This bioreactor was then subjected to a series of temperature reductions, and performance data were recorded after the mixed liquor had equilibrated to the test temperature. At least three days were allowed for temperature adjustment before performance data were obtained from the test bioreactor. Data collection continued for at least one week after the bioreactor had equilibrated to the test temperature. However, performance data may not represent a steady-state condition because the actual testing period at each experimental temperature was too short to assess long-term impact.

The test bioreactor average effluent quality during the temperature study is depicted in Table 7-2. Actual performance data obtained during the biooxidation temperature impact analysis are presented in Appendix I. These data indicate an apparently severe impact upon ammonia removal efficiency at a mixed liquor temperature of approximately 10°C. This effect is depicted in Figure 7-1. At this temperature bioreactor performance deteriorated rapidly, reducing both the level of ammonia utilization and the observed alkalinity usage. The volatile cell mass also was reduced, dropping from 79 percent to 63 percent of the total suspended solids under aeration. The observed average ammonia utilization was reduced from 0.086 mg NH_3-N per mg VSS per day to 0.024 mg NH_3-N per mg VSS per day. These effects intensified as the operational temperature was lowered further during the study. At an operational temperature of 6°C, ammonia utilization ceased. These effects occurred despite bioreactor operation at sludge ages in excess of 100 days.

The results presented in Table 7-2 show that nitrate formation was strongly inhibited at temperatures of 10°C or less under the conditions of the experiments. The microbial washout rate increased during this period and this may have been due to cell lyse. At no time during the study did nitrite buildup in the mixed liquor of the test bioreactor.

TABLE 7-2. BIOREACTOR EFFLUENT QUALITY DURING TEMPERATURE STUDY

Parameter[a]	22.0 ± 0.7°C (41)[b]		17.9 ± 0.2°C (12)		14.9 ± 0.2°C (7)		11.5 ± 0.7°C (8)		9.4 ± 0.4°C (14)		8.0 ± 0.3°C (6)		5.6 ± 1.2°C (8)	
	Mean	N[c]	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N
TOC	3	12	4	6	5	3	4	4	3	7	2	2	6	3
COD	18	12	13.3	6	23	3	30	4	27	7	33	2	23	3
NH_3-N	<1	13	0.12	6	0.07	3	0.08	4	209	8	252	2	278	5
NO_3-N	286	12	269	6	284	3	270	4	68	7	3.3	2	1.8	4
NO_2-N	<0.1	12	0.15	6	<0.1	3	0.16	4	0.22[d]	7	<0.1	2	<0.1	4
SCN	<1	12	1.05	6	1.03[e]	3	1.13	4	1.15[f]	6	1.1	2	11	5
Total CN	0.86	12	1.21	6	1.12	3	0.86	4	1.18	3	1.02	1	-	-

[a] All values as mg/L.

[b] Number of study days at given temperature.

[c] Number of observations.

[d] Not a true mean because five of the seven values reported as <0.1 mg/L.

[e] Not a true mean because two of the three values reported as <1 mg/L.

[f] Not a true mean because four of the six values reported as <1 mg/L.

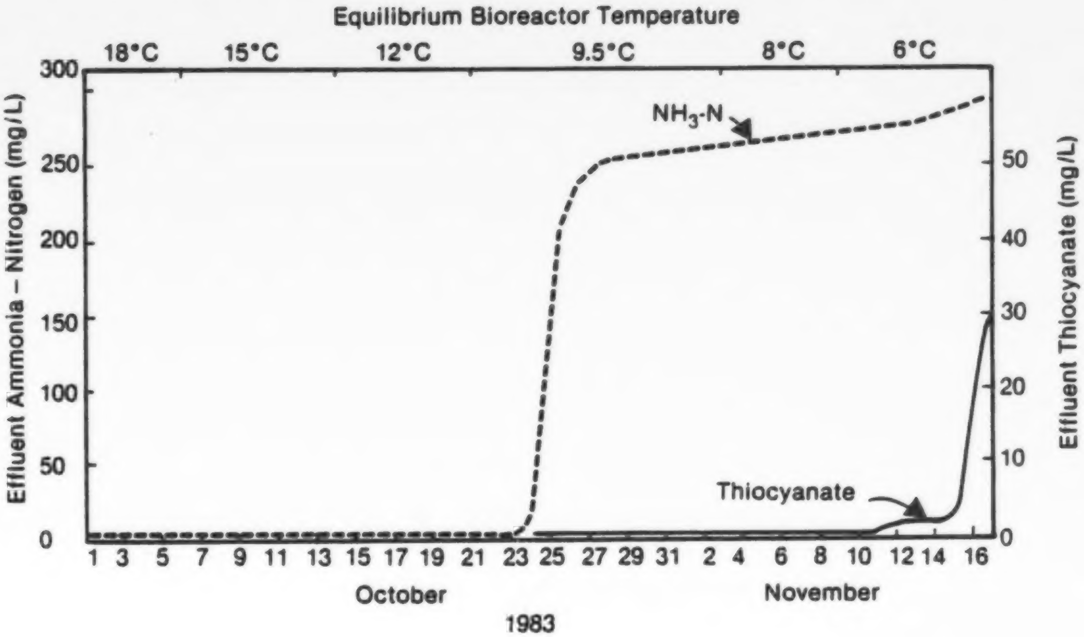

Figure 7-1. Impact of temperature on autotrophic biooxidation

Experimental data indicate that nitrification in the KRW activated sludge process is very sensitive to small changes in temperature over the range from 10°C to 12°C. This result corresponds to published data for temperature impacts upon nitrification of synthetic wastewater, albeit at much lower ammonia concentrations (Randall and Buth 1984).

An Arrhenius type of temperature relationship is described by:

$$k = Ae^{-E/RT} \tag{7-1}$$

where:

k is the maximum specific substrate removal coefficient at temperature T in °K,
E is the activation energy in cal/g-mol, and
R is the gas constant in cal/g-mol-°K.

This expression was evaluated using the substrate utilization parameter obtained from bioreactor testing in the temperature range between 22°C and 5.6°C. A plot of ln k vs 1/T is presented in Figure 7-2. This plot indicates that a portion of the data fits an Arrhenius function between temperatures of 12°C and 5°C. (Nitrification was virtually complete in the bioreactor between temperatures 12°C and 22°C; therefore, the apparent magnitude of the maximum specific substrate removal coefficient did not change in this temperature range.) However, the relationship is probably influenced by the effects of substrate (ammonia) inhibition which would call into question the validity of the reported value of the activation energy. This is apparent when the σ temperature coefficient (see Section 5) is determined from the same data group. Here the value of σ was calculated to be 1.46, which is disproportionately high and would suggest the influence of other factors besides temperature, namely substrate inhibition. The apparent severity of the temperature impact may also have resulted from the nature of the testing procedure in that the acclimation period at a given temperature was very

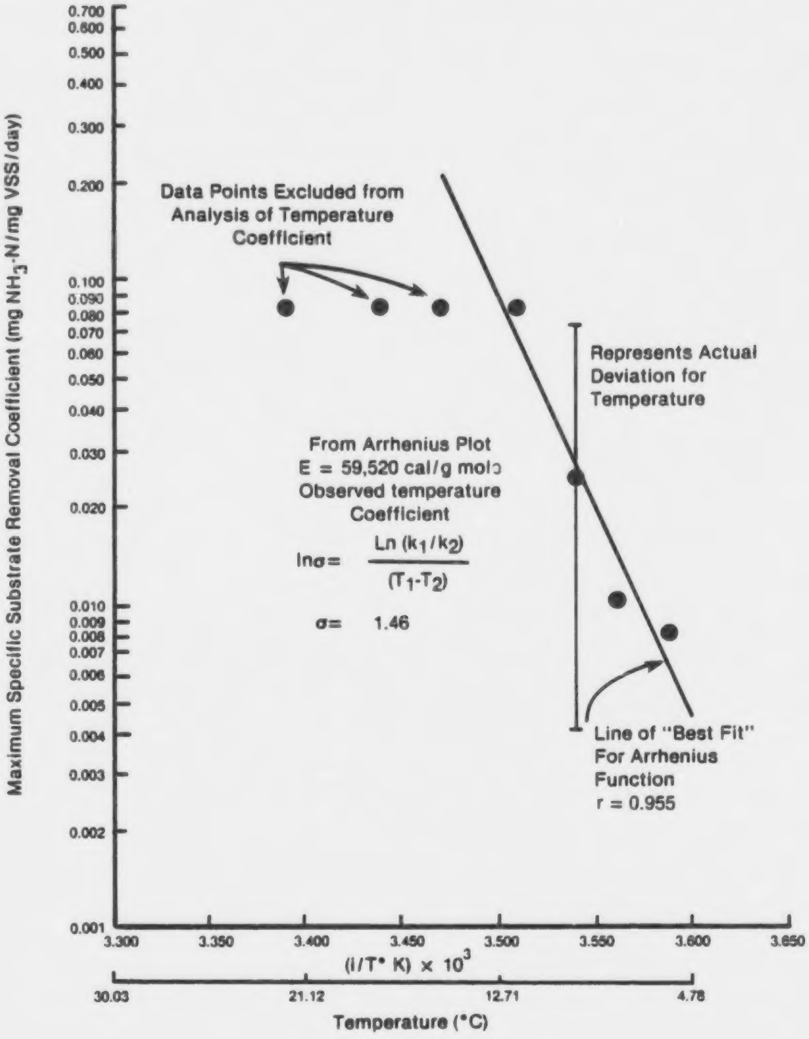

Figure 7-2. Arrhenius plot for a mixed culture treating KRW wastewaters

short. Therefore, the impacts could be described as transient occurrences that might ultimately change for the better.

Anthonisen et al. (1976) have shown that the inhibitory effects of ammonia are directly related to the concentration of the unionized form. The amount of free ammonia present in the KRW wastewater will depend on solution pH. It is reported that Nitrobacter is inhibited by free ammonia concentrations of 0.1 to 1.0 mg/L while concentrations greater than 10 mg/L are toxic to Nitrosomonas (Anthonisen et al. 1976). A range of concentrations was reported because microbial toxicity is a function of more than just the concentration of a toxic substance (e.g., pH and temperature also affect the observed toxicity of a given compound). The experimental temperature impact data seem to indicate that this was, in fact, the case with nitrification of the KRW wastewater. The severity of the temperature impact would imply a toxic shock effect rather than an effect due solely to temperature. This also would imply that there exists a coincidental and possibly synergistic effect between temperature and substrate (free ammonia) toxicity with nitrification of wastewaters that contain high concentrations of ammonia (i.e., >100 mg/L).

The observed thiocyanate removal efficiency deteriorated below a $6^{o}C$ bioreactor temperature (see Figure 7-1). There was no apparent reduction in thiocyanate biodegradation as the temperature was reduced until this temperature was reached, despite elevated levels of ammonia in the bioreactor. However, the observed thiocyanate utilization appeared to increase during the temperature study because the volatile cell mass under aeration was reducing coincident with the drop in ammonia utilization. (Biomass is determined by the volatile solids level in the bioreactor and this parameter does not differentiate between dead and live cells.)

7.2 NONSUBSTRATE ION TOXICITY STUDY

Pollutants which are common to most fluidized- and entrained-bed gasifier process wastewaters are chloride, fluoride, and boron. These nonsubstrate ions may exist at elevated concentrations in gasifier quench liquors and gas cooling condensates and are considered a potential source of problems for biological treatment. Their actual concentration in a given wastewater is coal dependent, with different equilibrium concentration ranges for each coal- type (e.g., bituminous, sub-bituminous, or lignite). Bituminous coal-derived wastewaters will be higher in chloride than either sub-bituminous coal or lignite-derived wastewaters. However, lignite-derived wastewaters will be higher in boron than wastewaters obtained from either sub-bituminous or bituminous coal. This portion of the microbial stress analysis involved an evaluation of biological treatment performance relative to elevated or "shock" loadings of these pollutants.

Since the quench liquors associated with the KRW coal gasification process are likely to be cycled during the quenching operation, certain ions (i.e., Cl^-, F^-, and BO_2^-) may be concentrated in the process wastewater. Control of these ions in the wastewater would largely be through predetermined quench liquor blowdowns which would be designed to restrict the concentration of a given pollutant (e.g., chloride) to within the prescribed limits. Given the nature of this cycling operation, certain pollutants in quench liquors from a commercial-scale facility would inevitably reach concentrations above those measured in process wastewaters from the KRW-PDU. Therefore, a "worst case" estimate of the probable maximum concentration associated with each of these pollutants in process wastewaters was projected and treatability testing with spiked KRW-PDU aqueous wastes was conducted.

A nonsubstrate ion toxicity study was performed with bioreactor activated sludges to document the impacts of increased concentrations of chloride, fluoride, and boron in the KRW wastewater on biooxidation treatment efficiency. The study was conducted with two continuously-fed, completely mixed bioreactors. One reactor served as a control, receiving feed with the ambient levels of the subject pollutants. The stress bioreactor was fed a wastewater with elevated concentrations of chloride, fluoride, and boron. These ions were introduced into the stress bioreactor in stages as is depicted in Figure

7-3. Target levels for the subject ions were 3,000 mg/L, 300 mg/L, and 150 mg/L for chloride, fluoride, and boron, respectively. The test ions were added as $CaCl_2$, $KF \cdot 2H_2O$, and H_3BO_3. All wastewater characteristics other than total dissolved solids and the subject ions were the same as the steady-state wastewater quality for the non-stressed system. All experimental data are presented in Appendix J.

The bioreactor operating conditions during the nonsubstrate ion toxicity study are presented in Table 7-3. The associated bioreactor performance data are summarized in Table 7-4. Little difference between the effluent ammonia and thiocyanate qualities of the control and stress bioreactors is apparent. Total dissolved solids levels in the stress bioreactor increased by 250 percent, apparently without impacting biological treatment efficiency. The mixed liquor suspended solids concentration in the stress bioreactor increased throughout the toxicity investigation. The equilibrium volatile solids level of the stress bioreactor was 35 percent of the mixed liquor suspended solids concentration, while the control bioreactor maintained a volatile solids level of 74 percent of the mixed liquor suspended solids under aeration. There also occurred a simultaneous improvement in the suspended solids settleability associated with the stress bioreactor activated sludges. These data indicate the presence of a chemical precipitate in the stress bioreactor mixed liquor which increased the density of the activated sludges. This precipitate (probably CaF_2) required that fluoride salts be added to the stress bioreactor feed in excess of the target concentration. The measured equilibrium concentration of fluoride averaged approximately 285 mg/L during the experimental observation.

Elevated concentrations of chloride, fluoride, and boron appeared to have little effect on ammonia and thiocyanate removal efficiency during biooxidation of the KRW wastewater. Therefore relative to the subject pollutants, the impact of coal-type on biological treatment performance should be negligible.

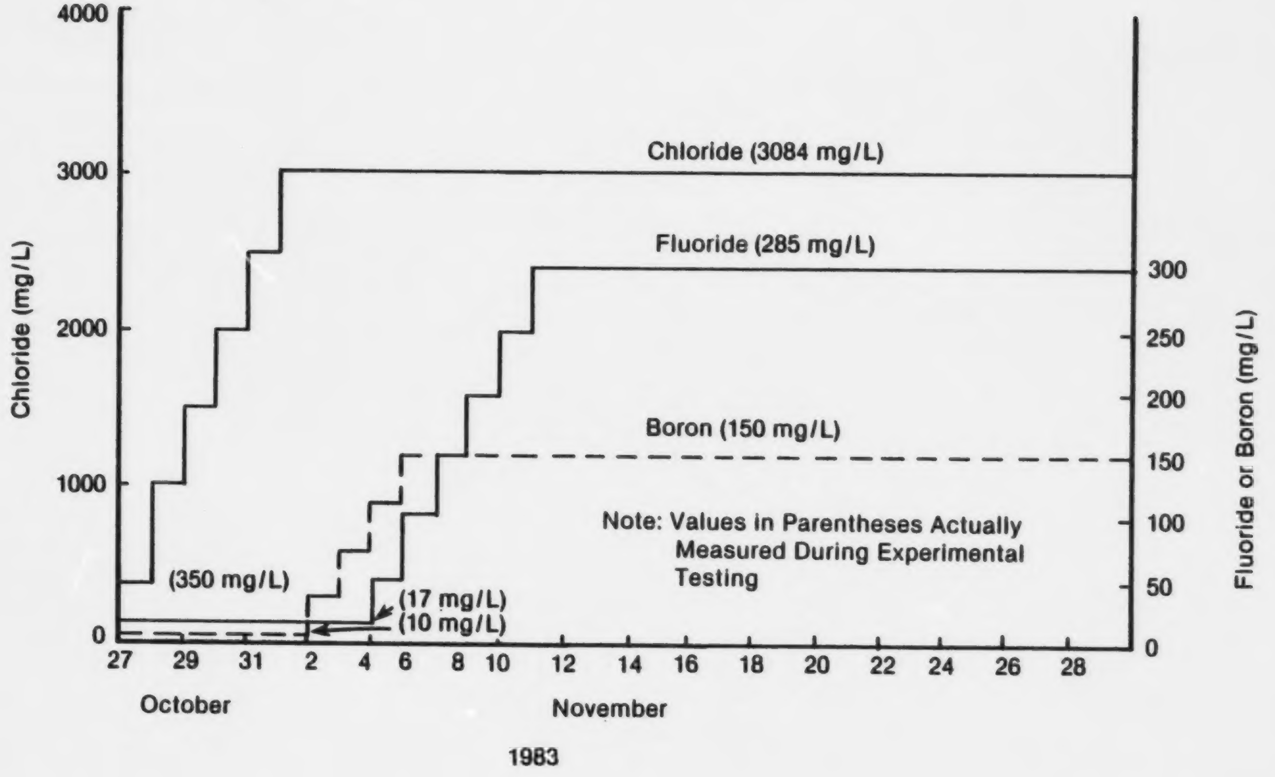

Figure 7-3. Nonsubstrate ion loading during stress tests

TABLE 7-3. BIOREACTOR OPERATION DURING NONSUBSTRATE ION STRESS STUDY

Parameter	Control Bioreactor		Stress Bioreactor	
Substrate Utilization				
Ammonia, $\frac{\text{mg NH}_3\text{-N}}{\text{mg VSS-day}}$	0.108 ± 0.016	(14)[a]	0.103 ± 0.014	(14)
Thiocyanate, $\frac{\text{mg SCN}}{\text{mg VSS-day}}$	0.048 ± 0.008	(14)	0.046 ± 0.007	(14)
Sludge age, days	155 ± 17	(11)	137 ± 23	(8)
MLSS, mg/L	3,672 ± 429	(11)	8,341 ± 1,319	(8)
MLVSS, mg/L	2,726 ± 370	(14)	2,913 ± 368	(14)
Sludge volume index, mL/gm	62 ± 9	(10)	24 ± 6	(8)
Total dissolved solids, mg/L	2,872 ± 185	(11)	7,286 ± 873	(10)
Chloride, mg/L	499[b]		3,087 ± 157	(4)
Fluoride, mg/L	17[b]		275 ± 23	(7)
Boron, mg/L	9.7[b]		146 ± 6	(8)
pH, pH units	7.0 ± 0.05	(36)	6.95 ± 0.05	(33)
Temperature, °C	20.5 ± 0.9	(34)	20.8 ± 1.1	(30)

[a] Number of data points are shown in parentheses.

[b] Results of characterization analysis dated 9/5/83 for steady-state bioreactor operation.

TABLE 7-4. NONSUBSTRATE ION STRESS STUDY PERFORMANCE DATA

	Influent Quality						Effluent Quality					
	Control Bioreactor			Stress Bioreactor			Control Bioreactor[b]			Stress Bioreactor[c]		
Parameter[a]	Mean	SD[d]	N[e]	Mean	SD	N	Mean	SD	N	Mean	SD	N
TOC	35	2.0	14	35	2.0	14	2	0.6	11	2	0.4	14
COD	172	16.4	13	184	28	12	15	8.3	11	40	17	13
NH_3-N	255	8.7	26	255	9.3	25	<1	-	31	<1	-	26
NO_3-N	<0.5	-	13	<0.5	-	13	276	10	11	278	8	13
NO_2-N	<0.1	-	13	<0.1	-	13	0.13[f]	-	11	0.11[f]	-	13
SCN	128	5.4	14	127	5	15	<1	-	12	<1	-	14
Total CN	1.19	0.07	5	1.17	0.08	5	1.05	0.09	3	1.0	0.16	5
TDS	297	61	13	6,031	657	10	2,872	185	11	7,286	873	10
TSS	5	5	12	100	91	10	9	2	11	19	7	10
VSS	2	3	12	16	12	10	5	2	11	8	5	10
Alkalinity ($CaCO_3$)	106	119	12	97	113	13	28	11	11	30	8	10
pH, pH units	6.95	1.0	38	6.61	0.65	42	7	0.05	36	6.95	0.05	33

[a] All values as mg/L except where otherwise noted.

[b] 20.5 ± 0.9°C (34).

[c] 20.8 ± 1.1°C (30).

[d] Standard deviation.

[e] Number of observations.

[f] Not a true mean because numerous values reported as <0.1 mg/L.

SECTION 8

REFERENCES

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APPENDIX A

ANALYSIS OF WASTEWATER FEED DURING STEADY-STATE TESTING

TABLE A-1. INFLUENT QUALITY

Date	pH	Total Alkalinity ($mg/L-CaCO_3$)	TOC (mg/L-C)	COD (mg/L)	Nitrate (mg/L-N)	Nitrite (mg/L-N)	Ammonia (mg/L-N)	Organic Nitrogen (mg/L-N)	Thiocyanate (mg/L-SCN)	Total Cyanide (mg/L-CN)	Total Phosphorus (mg/L-P)	TDS (mg/L)	TSS (mg/L)	VSS (mg/L)
07-25	7.10	—	—	—	—	—	—	—	—	—	—	—	—	—
07-26	7.00	—	—	—	—	—	255	—	—	—	—	—	—	—
07-27	7.05	—	—	—	—	—	—	—	—	—	—	—	—	—
07-28	7.10	300	175	370	—	—	255	—	—	—	—	5,635	—	—
07-29	7.00	—	44	—	—	—	255	0.32	145	—	—	—	—	—
07-30	7.10	—	—	—	—	—	280	—	—	—	—	—	—	—
07-31	7.10	—	—	—	—	—	255	—	—	—	—	—	—	—
08-01	6.80	60	39	242	—	—	255	—	—	—	—	300	—	—
08-02	6.00	—	—	—	—	—	255	—	—	—	—	—	—	—
08-03	7.20	—	—	—	—	—	265	—	142	1.5	—	—	—	—
08-04	7.20	72	40	—	—	—	—	—	—	—	—	305	—	—
08-05	6.50	—	—	—	—	—	260	—	—	—	—	—	3	2
08-06	6.00	—	—	—	—	—	250	—	—	—	—	—	—	—
08-07	6.95	—	—	—	—	—	—	—	—	—	—	—	—	—
08-08	6.45	26	39	216	—	—	265	—	146	—	—	298	4	<1
08-09	6.20	—	—	—	—	—	258	—	—	—	—	—	—	—
08-10	7.45	—	—	—	—	—	258	—	—	—	—	—	—	—
08-11	7.00	—	—	—	—	—	258	—	—	—	—	—	—	—
08-12	6.80	—	—	—	—	—	258	—	—	—	—	—	5	1

(continued)

TABLE A-1. (continued)

Date	pH	Total Alkalinity ($mg/L-CaCO_3$)	TOC (mg/L-C)	COD (mg/L)	Nitrate (mg/L-N)	Nitrite (mg/L-N)	Ammonia (mg/L-N)	Organic Nitrogen (mg/L-N)	Thiocyanate (mg/L-SCN)	Total Cyanide (mg/L-CN)	Total Phosphorus (mg/L-P)	TDS (mg/L)	TSS (mg/L)	VSS (mg/L)
08-13	7.25	—	—	—	—	—	265	—	—	—	—	—	—	—
08-14	7.00	91	40	223	0.8	<0.1	265	—	134	1.0	6.0	260	—	—
08-15	6.75	—	—	—	—	—	—	—	—	—	—	—	6	2
08-16	7.75	—	—	—	—	—	—	—	—	—	—	—	—	—
08-17	7.40	105	40	239	1.0	<0.1	255	—	136	1.37	—	265	4	1
08-18	7.30	—	—	—	—	—	—	—	—	—	—	—	—	—
08-19	7.10	—	—	—	—	—	—	—	—	—	—	—	—	—
08-20	7.00	—	—	—	—	—	—	—	—	—	—	—	4	2
08-21	6.75	98	39	196	0.70	<0.10	255	—	124	1.26	5.6	355	—	—
08-22	7.65	—	—	—	—	—	—	—	—	—	—	—	7	3
08-23	8.15	—	—	—	—	—	—	—	—	—	—	—	—	—
08-24	8.00	191	42	212	0.54	0.21	250	—	150	1.56	—	270	2	<1
08-25	7.95	—	—	—	—	—	—	—	—	—	—	—	—	—
08-26	7.90	—	—	—	—	—	—	—	—	—	—	—	—	—
08-27	7.85	—	—	—	—	—	—	—	—	—	—	—	4	2
08-28	7.75	96	36	208	0.47	0.21	253	—	127	1.33	—	260	—	—
08-29	7.55	—	—	—	—	—	—	—	—	—	—	—	<1	<1
08-30	7.55	—	—	—	—	—	—	—	—	—	—	—	—	—

(continued)

TABLE A-1. (continued)

Date	pH	Total Alkalinity (mg/L-CaCO$_3$)	TOC (mg/L-C)	COD (mg/L)	Nitrate (mg/L-N)	Nitrite (mg/L-N)	Ammonia (mg/L-N)	Organic Nitrogen (mg/L-N)	Thiocyanate (mg/L-SCN)	Total Cyanide (mg/L-CN)	Total Phosphorus (mg/L-P)	TDS (mg/L)	TSS (mg/L)	VSS (mg/L)
08-31	7.00	69	33	196	0.54	0.11	245	—	146	1.11	5.8	280	2	1
09-01	7.10	—	—	—	—	—	—	—	—	—	—	—	—	—
09-02	7.55	—	—	—	—	—	—	—	—	—	—	—	3	1
09-03	7.35	—	—	—	—	—	—	—	—	—	—	—	—	—
09-04	7.30	—	—	—	—	—	—	—	—	—	—	—	—	—
09-05	7.20	133	29	145	2.0	<0.10	270	—	148	1.05	—	245	4	3
09-06	7.50	—	—	—	—	—	—	—	—	—	—	—	—	—
09-07	7.30	103	—	152	—	—	—	—	—	—	—	—	4	2
09-08	7.15	102	29	146	3.4	<0.10	238	—	117	1.02	5.6	290	9	5
09-09	7.70	—	35	—	—	—	—	—	—	—	—	—	—	—
09-10	7.45	—	—	—	—	—	—	—	—	—	—	—	—	—
09-11	7.10	—	—	—	—	—	—	—	—	—	—	—	—	—
09-12	6.75	49	31	152	2.8	0.16	255	—	135	0.80	—	300	7	2
09-13	6.80	—	—	—	—	—	—	—	—	—	—	—	—	—
09-14	7.25	76	33	168	1.4	0.12	253	—	138	1.04	—	235	9	3
09-15	6.75	—	—	—	—	—	250	—	—	—	—	—	—	—
09-17	6.75	—	—	—	—	—	—	—	—	—	—	—	—	—
09-18	6.50	46	42	162	0.7	<0.1	250	—	127	1.19	4.2	280	—	—

(continued)

TABLE A-1. (continued)

Date	pH	Total Alkalinity (mg/L-CaCO$_3$)	TOC (mg/L-C)	COD (mg/L)	Nitrate (mg/L-N)	Nitrite (mg/L-N)	Ammonia (mg/L-N)	Organic Nitrogen (mg/L-N)	Thiocyanate (mg/L-SCN)	Total Cyanide (mg/L-CN)	Total Phosphorus (mg/L-P)	TDS (mg/L)	TSS (mg/L)	VSS (mg/L)
09-19	6.55	—	—	—	—	—	—	—	—	—	—	—	—	—
09-20	6.75	—	—	—	—	—	—	—	—	—	—	—	7	1
09-21	6.75	47	42	172	0.5	<0.1	248	—	125	1.11	—	225	3	2
09-22	6.95	—	—	—	—	—	—	—	—	—	—	—	—	—
09-23	6.75	—	—	—	—	—	—	—	—	—	—	—	2	2

APPENDIX B

BIOREACTOR EFFLUENT QUALITY DURING STEADY-STATE TESTING

TABLE B-1. BIOREACTOR 1 EFFLUENT QUALITY

Date	Temp. (^oC)	pH	Total Alkalinity ($mg/L-CaCO_3$)	TOC (mg/L)	COD (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	NH_3-N (mg/L)	Total Phosphorus (mg/L-P)	SCN (mg/L)	Total CN (mg/L)	TDS (mg/L)	MLSS TSS (mg/L)	MLSS VSS (mg/L)	TSS (mg/L)	VSS (mg/L)	Oxygen Uptake Rate (mg/L)/hr	ZSV (ft/hr)	Settle-ability (mL/30 min)	Volume (mL/day)	HRT (day)	0.50 N NaOH (mL/day)
7-25	22.5	7.30	–	–	–	–	–	–	–	–	–	–	2,240	1,910	–	–	–	–	–	–	–	–
7-26	22.5	7.25	–	–	–	–	–	<1	–	–	–	–	–	–	–	–	–	–	–	10,715	0.93	606
7-27	22.5	7.20	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	10,497	0.95	587
7-28	22.5	7.30	39	4	24	–	–	<1	–	–	–	7,830	–	–	–	–	–	–	–	10,485	0.95	501
7-29	22.5	7.00	–	–	–	–	–	–	–	–	–	–	2,680	2,150	10	7	10.20	–	–	10,506	0.95	422
7-30	22.0	7.30	–	–	–	–	–	<1	–	–	–	–	–	–	–	–	–	–	–	10,919	0.92	1,274
7-31	22.0	7.40	–	–	–	–	–	<1	–	–	–	–	–	–	–	–	–	–	–	10,973	0.91	791
8-01	23.0	7.30	26	4	56	–	–	<1	–	<1	–	3,320	–	–	–	–	–	–	–	11,446	0.87	862
8-02	23.0	7.30	–	–	–	–	–	<1	–	–	–	–	2,400	2,090	8	7	10.20	–	–	10,320	0.97	750
8-03	23.0	7.35	–	–	–	–	–	<1	–	–	–	–	–	–	–	–	–	–	–	9,920	1.01	850
8-04	28.0	7.35	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	11,000	0.91	800
8-05	23.0	7.35	–	–	–	–	–	<1	–	–	–	–	2,460	2,110	14	10	6.34	–	–	10,800	0.93	950
8-06	23.0	7.10	–	–	–	–	–	<1	–	–	–	–	–	–	–	–	–	–	–	11,316	0.88	889
8-07	22.5	7.35	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	11,270	0.89	750
8-08	22.5	7.10	18	2	29	–	–	<1	–	<1	–	3,040	2,500	2,110	9	4	7.20	–	–	10,960	0.91	914
8-09	22.5	7.30	–	–	–	–	–	<1	–	–	–	–	–	–	–	–	–	–	–	11,232	0.89	1,056
8-10	22.5	7.40	–	–	–	–	–	<1	–	–	–	–	–	–	–	–	–	–	–	11,478	0.87	939
8-11	23.0	7.40	–	–	–	–	–	<1	–	–	–	–	–	–	–	–	–	–	–	11,500	0.87	900
8-12	23.0	7.25	–	–	–	–	–	<1	–	–	–	–	2,620	2,120	9	5	7.70	–	–	11,282	0.89	990
8-13	23.0	7.35	–	–	–	–	–	<1	–	–	–	–	–	–	–	–	–	–	–	11,280	0.89	891

(continued)

TABLE B-1. (continued)

Date	Temp. (°C)	pH	Total Alkalinity (mg/L-CaCO$_3$)	TOC (mg/L)	COD (mg/L)	NO$_3$-N (mg/L)	NO$_2$-N (mg/L)	NH$_3$-N (mg/L)	Total Phosphorus (mg/L-P)	SCN (mg/L)	Total CN (mg/L)	TDS (mg/L)	MLSS TSS (mg/L)	MLSS VSS (mg/L)	TSS (mg/L)	VSS (mg/L)	Oxygen Uptake Rate (mg/L)/hr	ZSV (ft/hr)	Settle-ability (mL/30 min)	Volume (mL/day)	HRT (day)	0.50 N NaOH (mL/day)
8-14	23.0	7.25	28	<2	17	293	<0.10	<1	6.0	<1	0.83	2,993	-	-	-	-	-	-	-	11,164	0.90	971
8-15	23.0	7.35	-	-	-	-	-	-	-	-	-	-	2,740	2,230	7	5	4.76	7.36	265	11,260	0.89	974
8-16	22.5	7.30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,600	0.86	1,000
8-17	23.5	7.25	41	3	<10	280	0.16	<1	-	<1	0.90	2,965	2,750	2,300	8	5	6.24	8.66	265	10,763	0.93	698
8-18	23.0	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,116	0.90	909
8-19	23.0	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,134	0.99	834
8-20	22.5	7.35	-	-	-	-	-	-	-	-	-	-	2,420	1,850	6	5	5.80	8.42	250	11,597	0.86	858
8-21	23.5	7.30	49	<2	<10	283	<0.10	<1	3.0	<1	0.90	2,940	-	-	-	-	-	-	-	10,790	0.93	860
8-22	23.0	7.35	-	-	-	-	-	-	-	-	-	-	2,870	2,280	4	3	7.50	12.27	245	10,718	0.93	820
8-23	21.5	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,120	0.90	820
8-24	22.5	7.35	50	4	23	275	0.30	<1	-	<1	0.91	2,915	2,950	2,290	11	6	9.75	9.39	248	11,120	0.90	831
8-25	22.0	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,150	0.99	850
8-26	22.0	7.65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,229	0.89	903
8-27	22.0	7.00	-	-	-	-	-	-	-	-	-	-	2,970	2,300	8	5	13.8	9.75	240	11,782	0.85	820
8-28	22.5	7.00	23	3	18	308	<0.10	<1	1.6	<1	0.77	2,885	-	-	-	-	-	-	-	11,970	0.84	800
8-29	22.0	7.00	-	-	-	-	-	-	-	-	-	-	2,810	2,230	7	4	6.45	9.39	228	10,773	0.93	755
8-30	22.0	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,165	0.90	909
8-31	22.5	7.05	19	2	17	290	<0.10	<1	2.0	<1	0.80	2,925	2,910	2,300	4	4	6.60	10.47	225	10,764	0.93	891
9-01	22.0	7.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,540	0.87	817
9-02	22.0	7.00	-	-	-	-	-	-	-	-	-		2,970	2,340	9	6	6.60	11.91	217	11,120	0.90	778

(continued)

TABLE B-1. (continued)

Date	Temp. (°C)	pH	Total Alkalinity (mg/L-$CaCO_3$)	TOC (mg/L)	COD (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	NH_3-N (mg/L)	Total Phosphorus (mg/L-P)	SCN (mg/L)	Total CN (mg/L)	TDS (mg/L)	MLSS TSS (mg/L)	MLSS VSS (mg/L)	TSS (mg/L)	VSS (mg/L)	Oxygen Uptake Rate (mg/L)/hr	ZSV (ft/hr)	Settle-ability (mL/30 min)	Volume (mL/day)	HRT (day)	0.50 N NaOH (mL/day)
9-03	-	7.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,316	0.88	835
9-04	22.0	7.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,149	0.90	830
9-05	22.0	7.15	19	4	21	293	<0.10	<1	-	<1	0.86	2,965	2,685	2,060	16	10	11.40	12.45	215	11,135	0.88	833
9-06	22.0	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,025	0.91	877
9-07	22.5	7.00	-	-	-	-	-	-	-	-	-	-	2,640	2,080	12	7	9.72	12.27	207	11,030	0.91	803
9-08	22.0	7.10	22	3	12	258	<0.10	<1	2.3	<1	0.89	2,770	-	-	-	-	-	-	-	10,737	0.93	803
9-09	22.0	7.10	-	-	-	-	-	-	-	-	-	-	2,730	2,090	10	5	8.63	12.82	210	10,834	0.92	735
9-10	22.0	7.20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,091	0.90	760
9-11	22.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,019	0.91	803
9-12	22.0	7.05	33	3	31	303	<0.10	<1	-	<1	0.84	3,030	2,660	2,080	20	10	10.00	12.64	202	11,027	0.91	1,073
9-13	22.0	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,150	0.90	850
9-14	22.0	7.05	29	4	30	278	0.23	<1	-	<1	0.91	2,910	2,550	1,970	26	13	25.60	12.64	200	10,950	0.91	850
9-15	21.5	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,954	0.91	794
9-16	22.0	7.20	-	-	-	-	-	-	-	-	-	-	2,460	1,920	22	12	9.20	13.00	202	10,950	0.91	850
9-17	22.0	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,826	0.92	915
9-18	22.5	7.20	34	3	11	283	<0.1	<1	1.8	<1	1.0	2,940	-	-	-	-	-	-	-	10,718	0.93	885
9-19	22.0	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,861	0.92	824
9-20	22.0	7.15	-	-	-	-	-	-	-	-	-	-	2,510	1,960	16	9	24.60	13.72	185	10,744	0.93	817
9-21	20.0	7.05	38	3	9	283	<0.10	<1	-	<1	1.08	2,915	2,570	1,970	19	13	26.10	11.36	195	10,824	0.92	809
9-22	18.5	7.50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7,500	1.33	630
9-23	23.5	7.00	-	-	-	-	-	-	-	-	-	-	2,515	2,060	11	8	26.1	12.38	190	10,478	0.95	766

TABLE B-2. BIOREACTOR 2 EFFLUENT QUALITY

Date	Temp. (°C)	pH	Total Alkalinity (mg/L-$CaCO_3$)	TOC (mg/L)	COD (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	NH_3-N (mg/L)	Total Phosphorus (mg/L-P)	SCN (mg/L)	Total CN (mg/L)	TDS (mg/L)	MLSS TSS (mg/L)	MLSS VSS (mg/L)	TSS (mg/L)	VSS (mg/L)	Oxygen Uptake Rate (mg/L)/hr	ZSV (ft/hr)	Settle-ability (mL/30 min)	Volume (mL/day)	HRT (day)	0.50 N NaOH (mL/day)
7-25	22.5	7.20	-	-	-	-	-	-	-	-	-	-	3,230	2,670	-	-	-	-	-	-	-	-
7-26	22.5	7.25	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	10,919	0.92	586
7-27	22.5	7.20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,602	0.94	555
7-28	23.0	7.15	47	3	75	-	-	<1	-	-	-	7,845	-	-	-	-	-	-	-	10,616	0.94	559
7-29	23.5	7.00	-	-	-	-	-	-	-	-	-	-	3,610	2,940	10	6	10.40	-	-	10,456	0.96	633
7-30	22.5	7.30	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	4,259	2.35	365
7-31	23.0	7.40	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,163	0.90	904
8-01	23.0	7.40	26	4	81	-	-	<1	-	<1	-	3,810	-	-	-	-	-	-	-	11,643	0.86	935
8-02	23.5	7.35	-	-	-	-	-	<1	-	-	-	-	3,330	2,840	9	7	9.00	-	-	10,375	0.96	850
8-03	23.5	7.35	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	10,400	0.96	850
8-04	23.0	7.35	-	-	-	-	-	-	-	-	-	3,280	-	-	-	-	-	-	-	11,250	0.89	930
8-05	23.0	7.35	-	-	-	-	-	<1	-	-	-	-	3,230	2,820	13	10	6.77	-	-	11,200	0.89	990
8-06	23.0	7.15	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,360	0.88	978
8-07	23.0	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,240	0.89	940
8-08	23.0	7.15	21	<2	41	-	-	<1	-	<1	-	3,020	3,440	2,800	10	4	5.66	-	-	11,120	0.90	857
8-09	22.5	7.30	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,040	0.91	912
8-10	23.0	7.35	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,270	0.89	960
8-11	23.5	7.35	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,100	0.90	950
8-12	23.5	7.25	-	-	-	-	-	<1	-	-	-	-	3,790	3,070	7	3	7.80	-	-	11,035	0.91	940
8-13	23.5	7.35	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,040	0.91	939

(continued)

TABLE B-2. (continued)

Date	Temp. (°C)	pH	Total Alkalinity (mg/L-$CaCO_3$)	TOC (mg/L)	COD (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	NH_3-N (mg/L)	Total Phosphorus (mg/L-P)	SCN (mg/L)	Total CN (mg/L)	TDS (mg/L)	MLSS TSS (mg/L)	MLSS VSS (mg/L)	TSS (mg/L)	VSS (mg/L)	Oxygen Uptake Rate (mg/L)/hr	ZSV (ft/hr)	Settle-ability (ml/30 min)	Volume (ml/day)	HRT (day)	0.50 N NaOH (ml/day)
8-14	23.5	7.30	33	<2	<10	286	0.34	<1	5.8	<1	0.94	3,188	-	-	-	-	-	-	-	11,116	0.90	890
8-15	23.0	7.30	-	-	-	-	-	-	-	-	-	-	3,545	2,915	10	7	6.75	2.09	520	11,065	0.90	974
8-16	23.0	7.30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,500	0.87	920
8-17	23.5	7.30	42	<2	10	287	<0.10	<1	-	<1	1.01	2,935	3,550	2,950	8	4	5.85	1.11	590	10,735	0.93	847
8-18	23.0	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,200	0.89	925
8-19	23.0	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,134	0.99	789
8-20	23.0	7.35	-	-	-	-	-	-	-	-	-	-	3,910	3,370	7	6	4.95	2.26	460	11,984	0.83	954
8-21	23.5	7.30	52	<2	<10	284	<0.10	<1	3.0	<1	0.95	3,435	-	-	-	-	-	-	-	10,790	0.93	851
8-22	23.0	7.35	-	-	-	-	-	-	-	-	-	-	3,730	3,070	2	2	6.84	2.05	519	10,652	0.94	890
8-23	22.0	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,485	0.87	839
8-24	23.0	7.35	47	4	23	290	<0.10	<1	-	<1	0.94	2,955	3,840	3,100	8	5	8.62	1.91	520	11,241	0.89	864
8-25	22.5	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,450	0.96	930
8-26	22.5	6.40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,357	0.88	948
8-27	23.0	7.00	-	-	-	-	-	-	-	-	-	-	3,900	3,150	10	7	8.85	3.38	480	11,782	0.85	769
8-28	23.5	7.00	28	<2	12	305	<0.10	<1	1.6	<1	0.65	2,905	-	-	-	-	-	-	-	12,050	0.83	800
8-29	22.0	7.00	-	-	-	-	-	-	-	-	-	-	3,580	2,930	6	4	7.35	2.83	445	10,894	0.92	811
8-30	22.5	7.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,863	0.92	819
8-31	23.0	7.05	23	2	16	295	<0.10	<1	2.0	<1	0.75	2,940	3,630	2,960	7	4	8.31	3.25	440	10,958	0.91	841
9-01	22.5	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,643	0.86	853
9-02	22.5	7.00	-	-	-	-	-	-	-	-	-	-	3,870	3,070	7	5	8.27	3.18	380	10,898	0.92	862

(continued)

TABLE B-2. (continued)

Date	Temp. (°C)	pH	Total Alkalinity (mg/L-CaCO$_3$)	TOC (mg/L)	COD (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	NH_3-N (mg/L)	Total Phosphorus (mg/L-P)	SCN (mg/L)	Total CN (mg/L)	TDS (mg/L)	MLSS TSS (mg/L)	MLSS VSS (mg/L)	TSS (mg/L)	VSS (mg/L)	Oxygen Uptake Rate (mg/L)/hr	ZSV (ft/hr)	Settle-ability (mL/30 min)	Volume (mL/day)	HRT (day)	0.50 N NaOH (mL/day)
9-03	-	7.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,920	0.91	806
9-04	22.5	7.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,169	0.90	805
9-05	22.5	7.15	21	4	25	290	<0.10	<1	-	<1	0.88	2,970	3,675	2,890	22	12	11.01	4.14	395	11,484	0.87	833
9-06	22.5	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,963	0.91	774
9-07	23.0	7.05	-	-	-	-	-	-	-	-	-	-	3,500	2,770	14	10	10.95	4.69	351	11,132	0.90	791
9-08	22.5	7.10	27	3	12	273	<0.10	<1	2.3	<1	0.85	2,830	-	-	-	-	-	-	-	11,038	0.91	728
9-09	23.0	7.10	-	-	-	-	-	-	-	-	-	-	3,870	3,080	11	6	9.60	4.81	363	10,864	0.92	627
9-10	22.0	7.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,046	0.91	778
9-11	23.0	7.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,936	0.91	835
9-12	22.0	7.10	24	3	30	296	<0.10	<1	-	<1	0.85	3,010	3,450	2,690	80	10	10.32	5.05	330	10,972	0.91	876
9-13	22.0	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,100	0.91	850
9-14	22.0	7.05	19	3	18	278	<0.10	<1	-	<1	0.98	2,990	3,470	2,720	19	11	9.20	5.14	330	10,900	0.92	820
9-15	22.0	7.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,646	0.94	844
9-16	22.0	7.05	-	-	-	-	-	-	-	-	-	-	3,520	2,770	20	10	9.09	5.96	298	10,850	0.92	950
9-17	22.0	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,740	0.93	819
9-18	22.5	7.00	18	3	11	273	<0.1	1.9	<1		0.97	2,955	-	-	-	-	-	-	-	10,905	0.92	867
9-19	22.0	6.95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,861	0.92	873
9-20	22.0	7.05	-	-	-	-	-	-	-	-	-	-	3,440	2,750	16	9	16.8	6.86	305	10,969	0.91	837
9-21	20.0	7.05	18	3	26	275	<0.1	<1	-	<1	1.0	2,910	3,480	2,720	22	14	17.5	6.06	308	10,993	0.91	871
9-22	19.0	7.05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,950	0.91	356
9-23	23.5	7.05	-	-	-	-	-	-	-	-	-	-	3,575	2,835	12	8	17.5	6.40	320	10,621	0.94	889

TABLE B-3. BIOREACTOR 3 EFFLUENT QUALITY

Date	Temp. (°C)	pH	Total Alkalinity (mg/L-$CaCO_3$)	TOC (mg/L)	COD (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	NH_3-N (mg/L)	Total Phosphorus (mg/L-P)	SCN (mg/L)	Total CN (mg/L)	TDS (mg/L)	MLSS TSS (mg/L)	MLSS VSS (mg/L)	TSS (mg/L)	VSS (mg/L)	Oxygen Uptake Rate (mg/L)/hr	ZSV (ft/hr)	Settle-ability (mL/30 min)	Volume (mL/day)	HRT (day)	0.50 N NaOH (mL/day)
7-25	22.5	7.15	-	-	-	-	-	-	-	-	-	-	5,150	4,050	-	-	-	-	-	-	-	-
7-26	22.5	7.15	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,482	0.87	697
7-27	22.0	7.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,664	0.94	565
7-28	22.5	7.15	72	5	41	-	-	<1	-	-	-	7,340	-	-	-	-	-	-	-	10,616	0.94	668
7-29	22.0	7.00	-	-	-	-	-	-	-	-	-	-	4,630	3,770	13	8	22.80	-	-	10,586	0.94	633
7-30	22.0	7.30	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,039	0.91	850
7-31	22.0	7.30	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,140	0.90	1,129
8-01	23.0	7.25	29	4	65	-	-	<1	-	<1	-	3,330	-	-	-	-	-	-	-	11,483	0.87	738
8-02	23.0	7.15	-	-	-	-	-	<1	-	-	-	-	4,430	3,720	7	6	10.08	-	-	10,970	0.91	900
8-03	22.5	7.30	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	10,840	0.92	900
8-04	22.5	7.30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,250	0.89	900
8-05	22.5	6.00	-	-	-	-	-	3	-	-	-	-	4,520	3,720	11	8	111	-	-	10,950	0.91	700
8-06	22.5	7.05	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	9,956	1.00	889
8-07	22.5	7.30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,100	0.90	1,000
8-08	22.5	7.15	20	<2	73	-	-	<1	-	<1	-	2,995	4,570	3,740	10	5	6.32	-	-	10,857	0.92	857
8-09	22.5	7.25	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,328	0.88	816
8-10	22.5	7.25	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,374	0.88	1,043
8-11	23.0	7.35	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,100	0.90	900
8-12	23.0	7.25	-	-	-	-	-	<1	-	-	-	-	4,560	3,740	12	6	6.60	-	-	11,381	0.88	891
8-13	23.0	7.35	-	-	-	-	-	<1	-	-	-	-	-	-	-	-	-	-	-	11,314	0.88	960

(continued)

TABLE B-3. (continued)

Date	Temp. (°C)	pH	Total Alkalinity (mg/L-$CaCO_3$)	TOC (mg/L)	COD (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	NH_3-N (mg/L)	Total Phosphorus (mg/L-P)	SCN (mg/L)	Total CN (mg/L)	TDS (mg/L)	MLSS TSS (mg/L)	MLSS VSS (mg/L)	TSS (mg/L)	VSS (mg/L)	Oxygen Uptake Rate (mg/L)/hr	ZSV (ft/hr)	Settle-ability (mL/30 min)	Volume (mL/day)	HRT (day)	0.50 N NaOH (mL/day)
8-14	23.0	7.25	35	<2	49	287	<0.10	<1	5.8	<1	0.82	3,153	-	-	-	-	-	-	-	11,407	0.88	971
8-15	22.5	7.25	-	-	-	-	-	-	-	-	-	-	4,580	3,740	7	6	6.99	0.68	785	11,238	0.89	974
8-16	22.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,000	0.91	950
8-17	23.0	7.25	43	3	20	283	<0.10	<1	-	<1	0.99	2,965	4,760	3,890	8	5	6.56	0.39	800	11,161	0.90	947
8-18	22.5	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,116	0.90	909
8-19	22.5	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,199	0.98	834
8-20	22.5	7.25	-	-	-	-	-	-	-	-	-	-	4,750	3,880	11	8	6.00	0.68	690	11,887	0.84	858
8-21	22.5	7.25	47	<2	<10	283	<0.10	<1	3.0	<1	0.87	2,970	-	-	-	-	-	-	-	10,831	0.92	860
8-22	22.5	7.25	-	-	-	-	-	-	-	-	-	-	4,680	3,820	6	4	6.48	0.99	682	10,731	0.93	820
8-23	21.5	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,576	0.86	820
8-24	22.5	7.25	43	2	16	300	<0.10	<1	-	<1	0.62	2,965	4,620	3,770	11	7	8.108	0.70	748	11,518	0.87	797
8-25	22.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,200	0.98	930
8-26	22.0	7.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,486	0.87	858
8-27	22.0	7.10	-	-	-	-	-	-	-	-	-	-	4,650	3,790	10	7	8.70	1.34	720	12,000	0.83	922
8-28	22.5	7.10	28	2	15	305	<0.10	<1	1.6	<1	0.48	2,925	-	-	-	-	-	-	-	12,150	0.82	700
8-29	22.0	7.15	-	-	-	-	-	-	-	-	-	-	4,760	3,850	6	4	8.56	1.30	682	11,093	0.90	755
8-30	22.0	7.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,217	0.89	896
8-31	22.5	7.15	24	2	22	285	<0.10	<1	2.0	<1	0.86	2,940	4,780	3,870	7	5	9.20	1.08	700	11,152	0.90	934
9-01	21.5	7.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,234	0.89	817
9-02	21.5	7.15	-	-	-	-	-	-	-	-	-	-	4,610	3,660	8	5	10.29	0.70	763	10,030	1.00	945

(continued)

TABLE B-3. (continued)

Date	Temp. (°C)	pH	Total Alkalinity (mg/L-CaCO$_3$)	TOC (mg/L)	COD (mg/L)	NO$_3$-N (mg/L)	NO$_2$-N (mg/L)	NH$_3$-N (mg/L)	Total Phosphorus (mg/L-P)	SCN (mg/L)	Total CN (mg/L)	TDS (mg/L)	MLSS TSS (mg/L)	MLSS VSS (mg/L)	TSS (mg/L)	VSS (mg/L)	Oxygen Uptake Rate (mg/L)/hr	ZSV (ft/hr)	Settle-ability (mL/30 min)	Volume (mL/day)	HRT (day)	0.50 N NaOH (mL/day)
9-03	-	7.15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	112,970	0.89	867
9-04	21.5	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,198	0.89	859
9-05	22.0	7.25	27	3	25	283	<0.10	<1	-	<1	0.90	2,995	4,620	3,660	18	11	18.60	0.59	770	11,556	0.87	869
9-06	22.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,148	0.90	877
9-07	22.5	7.25	-	-	-	-	-	-	-	-	-	-	4,770	3,800	14	7	41.16	2.36	577	11,132	0.90	868
9-08	22.0	7.25	39	4	19	267	<0.10	<1	2.3	<1	0.85	2,855	-	-	-	-	-	-	-	11,088	0.90	702
9-09	22.0	7.25	-	-	-	-	-	-	-	-	-	-	5,010	3,910	10	6	11.28	0.70	738	10,707	0.93	686
9-10	22.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,627	0.86	850
9-11	22.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,082	0.90	887
9-12	22.0	7.25	38	3	11	295	<0.10	<1	-	<1	0.81	3,050	4,710	3,740	25	14	12.15	0.75	710	11,093	0.90	1,040
9-13	22.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,250	0.89	850
9-14	22.0	7.25	37	3	<10	275	<0.10	<1	-	<1	0.91	3,015	4,700	3,710	21	12	14.40	0.75	736	10,900	0.92	900
9-15	21.5	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,974	0.91	844
9-16	22.0	7.25	-	-	-	-	-	-	-	-	-	-	4,820	3,820	21	11	17.49	0.58	763	11,000	0.91	900
9-17	22.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,884	0.92	915
9-18	22.5	7.25	38	3	12	285	<0.1	<1	1.8	<1	1.13	2,970	-	-	-	-	-	-	-	10,812	0.92	839
9-19	22.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11,103	0.90	873
9-20	22.0	7.25	-	-	-	-	-	-	-	-	-	-	4,580	3,600	11	7	8.73	0.58	770	10,907	0.92	817
9-21	20.0	7.25	37	3	11	288	<0.1	<1	-	<1	1.02	2,910	4,900	3,750	17	11	14.4	0.54	778	11,057	0.90	893
9-22	19.0	7.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10,400	0.96	909
9-23	23.0	7.25	-	-	-	-	-	-	-	-	-	-	4,695	3,660	13	9	14.4	0.55	770	10,660	0.94	967

APPENDIX C

OXYGEN UTILIZATION ANALYSIS

TABLE C-1. OXYGEN UTILIZATION ANALYSIS

Oxygen Demand

mg O_2 / mg VSS-day

	Bioreactor 1		Bioreactor 2		Bioreactor 3	
Date	Immediate	Initial	Immediate	Initial	Immediate	Initial
07-29-83	1.955	0.505	1.685	0.350	2.254	0.426
08-02-83	1.585	0.268	1.045	0.168	-	0.126
08-05-83	2.225	0.257	2.083	0.172	2.717	0.648
08-08-83	0.177[a]	0.133[a]	0.072[a]	0.079[a]	0.077	0.073[a]
08-12-83	0.272[a]	0.151[a]	0.253[a]	0.075[a]	0.023	0.053[a]
08-15-83	0.013[a]	0.048[a]	0.059[a]	0.085[a]	0.023	0.040[a]
08-17-83	0.050[a]	0.075[a]	0.029[a]	0.036[a]	0.170	0.099[a]
08-20-83	0.016[a]	0.080[a]	-	0.029[a]	0.037	0.040[a]
08-22-83	0.038[a]	0.083[a]	0.047[a]	0.056[a]	0.038	0.041[a]
08-24-83	2.390	0.349	2.174	0.244	1.459	0.170
08-27-83	-	0.150	-	0.674	-	0.456
08-29-83	2.596	0.317	2.516	0.191	1.750	0.143
08-31-83	3.243	0.308	1.956	0.203	1.942	0.202
09-02-83	3.508	0.324	1.351	0.241	1.377	0.160
09-05-83	4.054	0.427	1.834	0.208	2.770	0.299
09-07-83	3.046	0.372	2.267	0.261	4.002	0.340

(continued)

TABLE C-1. (continued)

Oxygen Demand

mg O_2 / mg VSS-day

	Bioreactor 1		Bioreactor 2		Bioreactor 3	
Date	Immediate	Initial	Immediate	Initial	Immediate	Initial
09-09-83	2.301	0.303	2.151	0.195	2.460	0.244
09-12-83	3.725	0.498	3.608	0.288	0.490	0.178
09-14-83	4.620	0.714	1.715	0.178	1.607	0.326
09-16-83	2.655	0.450	0.988	0.190	1.191	0.198
09-20-83	2.469	0.428	1.665	0.275	1.304	0.178
09-21-83	1.520	0.551	0.392	0.245	1.935	0.261
09-23-83	1.817	0.387	0.610	0.339	2.007	0.249
Mean[b]	2.732	0.389	1.753	0.260	1.951	0.271
Std. Dev.	0.9	0.132	0.783	0.12	0.831	0.136
Number of data	16	17	16	17	15	17
Mean[c]	2.919	0.398	1.787	0.267	1.869	0.243
Std. Dev.	0.89	0.133	0.845	0.126	0.862	0.088
Number of data	13	14	13	14	13	14

(continued)

TABLE C-1. (continued)

	Oxygen Demand mg O_2 / mg VSS-day					
	Bioreactor 1		Bioreactor 2		Bioreactor 3	
Date	Immediate	Initial	Immediate	Initial	Immediate	Initial
Mean[d]	0.094	0.095	0.092	0.06	0.061	0.058
Std. Dev.	0.106	0.039	0.091	0.024	0.057	0.024
Number of data	6	6	5	6	6	6

[a] Oxygen uptakes after 8 - 10 minutes of aeration without feed.

[b] All data included.

[c] Data exclusive of apparent endogenous oxygen demand.

[d] Endogenous oxygen demand.

APPENDIX D

BIOREACTOR OPERATING DATA

TABLE D-1. BIOREACTOR 1 OPERATING DATA

Date	θ [d]	X [mg VSS/L]	X_e [mg VSS/L]	$Q_wX + Q_eX_e$ [mg VSS/d]	θ_c [d]	$1/\theta_c$ [d^{-1}]	R_r^* [mg O_2/L-d]	R_r/X [mg O_2/mg VSS-d]	ZSV [gpd/ft^2]	SVI [mLs/gm]
08-12	0.87	2,120	5	343	61.9	0.0162	184.8	0.087	-	-
08-13	0.89	-	-	-	-	-	-	-	-	-
08-14	0.90	-	-	-	-	-	-	-	-	-
08-15	0.89	2,230	5	357	62.4	0.0160	114.2	0.051	1,321	95
08-16	0.86	-	-	-	-	-	-	-	-	-
08-17	0.93	2,300	5	364	63.1	0.0158	149.8	0.065	1,555	92
08-18	0.90	-	-	-	-	-	-	-	-	-
08-19	0.99	-	-	-	-	-	-	-	-	-
08-20	0.86	1,850	5	308	60.1	0.0166	139.2	0.075	1,512	108
08-21	0.93	-	-	-	-	-	-	-	-	-
08-22	0.93	2,280	3	340	67.1	0.0149	164.2	0.079	2,203	86
08-23	0.90	-	-	-	-	-	-	-	-	-
08-24	0.90	2,290	6	375.9	60.9	0.0164	223.2	0.097	1,686	87
08-25	0.99	-	-	-	-	-	-	-	-	-
08-26	0.89	-	-	-	-	-	-	-	-	-
08-27	0.85	2,300	5	369.4	62.3	0.0161	331.2	0.144	1,750	83
08-28	0.84	-	-	-	-	-	-	-	-	-
08-29	0.93	2,230	4	344.1	64.8	0.0154	154.8	0.069	1,686	82
08-30	0.90	-	-	-	-	-	-	-	-	-
08-31	0.93	2,300	4	353.6	65.1	0.0154	158.4	0.069	1,880	79
09-01	0.87	-	-	-	-	-	-	-	-	-
09-02	0.90	2,340	6	382.6	61.2	0.0164	158.4	0.068	2,138	75
09-03	0.88	-	-	-	-	-	-	-	-	-
09-04	0.90	-	-	-	-	-	-	-	-	-
09-05	0.88	2,060	10	389.5	52.9	0.0189	273.6	0.133	2,235	83
09-06	0.91	-	-	-	-	-	-	-	-	-
09-07	0.91	2,080	7	358.0	58.1	0.0172	233.3	0.112	2,203	80
09-08	0.93	-	-	-	-	-	-	-	-	-
09-09	0.92	2,090	5	336.3	62.1	0.0161	207.1	0.099	2,302	80
09-10	0.90	-	-	-	-	-	-	-	-	-
09-11	0.91	-	-	-	-	-	-	-	-	-
09-12	0.91	2,080	10	391.1	53.2	0.0188	240.0	0.115	2,269	78
09-13	0.90	-	-	-	-	-	-	-	-	-

(continued)

TABLE D-1. (continued)

Date	θ [d]	X [mg VSS/L]	X_e [mg VSS/L]	$Q_wX + Q_eX_e$ [mg VSS/d]	θ_c [d]	$1/\theta_c$ [d^{-1}]	R_r[a] [mg O_2/L-d]	R_r/X [mg O_2/mg VSS-d]	ZSV [gpd/ft^2]	SVI [mLs/gm]
09-14	0.91	1,970	13	408.3	48.2	0.0207	614.4[b]	0.312	2,269	82
09-15	0.91	-	-	-	-	-	-	-	-	-
09-16	0.91	1,920	12	390.6	49.1	0.0203	220.8	0.115	2,334	84
09-17	0.92	-	-	-	-	-	-	-	-	-
09-18	0.93	-	-	-	-	-	-	-	-	-
09-19	0.92	-	-	-	-	-	-	-	-	-
09-20	0.93	1,960	9	361.3	54.2	0.018	590.4[b]	0.301	2,463	75
09-21	0.92	1,970	13	406.6	48.5	0.021	626.4[b]	0.318	2,039	79
09-22	1.33	-	-	-	-	-	-			
09-23	0.95	2,060	8	361.9	56.9	0.017	626.4[b]	0.304	2,223	74

[a] Equilibrium demand.

[b] Initial demand.

TABLE D-2. BIOREACTOR 2 OPERATING DATA

Date	θ [d]	X [mg VSS/L]	X_e [mg VSS/L]	$Q_w X + Q_e X_e$ [mg VSS/d]	θ_c [d]	$1/\theta_c$ [d^{-1}]	R_r^a [mg O_2/L-d]	R_r/X [mg O_2/mg VSS-d]	ZSV [gpd/ft^2]	SVI [mLs/gm]
08-12	0.91	3,070	3	248	124	0.0081	187.2	0.061	-	-
08-13	0.91	-	-	-	-	-	-	-	-	-
08-14	0.90	-	-	-	-	-	-	-	-	-
08-15	0.90	2,910	7	281	103.5	0.0097	162.0	0.056	375	146
08-16	0.87	-	-	-	-	-	-	-	-	-
08-17	0.93	2,950	4	249	118	0.0085	140.4	0.047	199	163
08-18	0.89	-	-	-	-	-	-	-	-	-
08-19	0.99	-	-	-	-	-	-	-	-	-
08-20	0.83	3,370	6	308	109.5	0.0091	118.8	0.035	406	111
08-21	0.93	-	-	-	-	-	-	-	-	-
08-22	0.94	3,070	2	236	130	0.0077	155.5	0.053	368	138
08-23	0.87	-	-	-	-	-	-	-	-	-
08-24	0.89	3,100	5	273	113.5	0.0088	234.2	0.076	343	137
08-25	0.96	-	-	-	-	-	-	-	-	-
08-26	0.88	-	-	-	-	-	-	-	-	-
08-27	0.85	3,150	7	303	104	0.0096	212.4	0.067	607	124
08-28	0.83	-	-	-	-	-	-	-	-	-
08-29	0.92	2,930	4	249	118	0.0085	176.4	0.060	508	124
08-30	0.92	-	-	-	-	-	-	-	-	-
08-31	0.91	2,960	4	251	118	0.0085	199.4	0.067	583	121
09-01	0.86	-	-	-	-	-	-	-	-	-
09-02	0.92	3,070	5	269	114	0.0087	198.5	0.065	571	101
09-03	0.91	-	-	-	-	-	-	-	-	-
09-04	0.90	-	-	-	-	-	-	-	-	-
09-05	0.87	2,890	12	340	85	0.0118	264.2	0.091	743	112
09-06	0.91	-	-	-	-	-	-	-	-	-
09-07	0.90	2,770	10	305	90.8	0.0110	262.8	0.095	842	104
09-08	0.91	-	-	-	-	-	-	-	-	-
09-09	0.92	3,080	6	280	110	0.0091	230.4	0.075	863	96
09-10	0.91	-	-	-	-	-	-	-	-	-
09-11	0.91	-	-	-	-	-	-	-	-	-
09-12	0.91	2,690	10	298	90.3	0.0111	247.7	0.092	906	100
09-13	0.91	-	-	-	-	-	-	-	-	-

(continued)

TABLE D-2. (continued)

Date	Θ [d]	X [mg VSS/L]	X_e [mg VSS/L]	$Q_wX + Q_eX_e$ [mg VSS/d]	Θ_c [d]	$1/\Theta_c$ [d^{-1}]	R_r[a] [mg O_2/L-d]	R_r/X [mg O_2/mg VSS-d]	ZSV [gpd/ft^2]	SVI [mLs/gm]
09-14	0.92	2,720	11	310	87.7	0.0114	220.8	0.081	923	99
09-15	0.94	-	-	-	-	-	-	-	-	-
09-16	0.92	2,770	10	302	91.6	0.0109	225.8	0.0815	1,070	88
09-17	0.93	-	-	-	-	-	-	-	-	-
09-18	0.92	-	-	-	-	-	-	-	-	-
09-19	0.92	-	-	-	-	-	-	-	-	-
09-20	0.91	2,750	9	291.2	94.4	0.0106	403.2[b]	0.147	1,232	90
09-21	0.91	2,720	14	344.3	79	0.013	420.0[b]	0.154	1,088	92
09-22	0.91	-	-	-	-	-	-	-	-	-
09-23	0.94	2,835	8	283.4	100	0.010	420.0[b]	0.148	1,149	92

[a] Equilibrium demand.

[b] Initial demand.

TABLE D-3. BIOREACTOR 3 OPERATING DATA

Date	θ [d]	X [mg VSS/L]	X_e [mg VSS/L]	$Q_wX + Q_eX_e$ [mg VSS/d]	θ_c [d]	$1/\theta_c$ [d^{-1}]	R_r[a] [mg O_2/L-d]	R_r/X [mg O_2/mg VSS-d]	ZSV [gpd/ft^2]	SVI [mLs/gm]
08-12	0.88	3,740	6	237	158	0.0063	158.4	0.042	-	-
08-13	0.88	-	-	-	-	-	-	-	-	-
08-14	0.88	-	-	-	-	-	-	-	-	-
08-15	0.89	3,740	6	236	159	0.0063	167.8	0.045	122	171
08-16	0.91	-	-	-	-	-	-	-	-	-
08-17	0.90	3,890	5	231	169	0.0059	157.4	0.0405	70	168
08-18	0.90	-	-	-	-	-	-	-	-	-
08-19	0.98	-	-	-	-	-	-	-	-	-
08-20	0.84	3,880	8	270	144	0.0070	144	0.037	122	145
08-21	0.92	-	-	-	-	-	-	-	-	-
08-22	0.93	3,820	4	215	178	0.0056	180	0.041	178	146
08-23	0.86	-	-	-	-	-	-	-	-	-
08-24	0.87	3,770	7	250	151	0.0066	175	0.046	126	161
08-25	0.98	-	-	-	-	-	-	-	-	-
08-26	0.87	-	-	-	-	-	-	-	-	-
08-27	0.83	3,790	7	254.5	149	0.0067	208.8	0.055	240	155
08-28	0.82	-	-	-	-	-	-	-	-	-
08-29	0.90	3,850	4	218	177	0.0057	205.4	0.053	0.233	144
08-30	0.89	-	-	-	-	-	-	-	-	-
08-31	0.90	3,870	5	230	168	0.0059	220.8	0.057	194	148
09-01	0.89	-	-	-	-	-	-	-	-	-
09-02	1.0	3,660	5	215	170	0.0059	247	0.067	126	170
09-03	0.89	-	-	-	-	-	-	-	-	-
09-04	0.89	-	-	-	-	-	-	-	-	-
09-05	0.87	3,660	11	292	125	0.0080	470.9[b]	0.129	106	171
09-06	0.90	-	-	-	-	-	-	-	-	-
09-07	0.90	3,800	7	249	153	0.0066	987.8[b]	0.260	424	124
09-08	0.90	-	-	-	-	-	-	-	-	-
09-09	0.93	3,910	6	240	163	0.0061	270.7	0.069	126	154
09-10	0.86	-	-	-	-	-	-	-	-	-
09-11	0.90	-	-	-	-	-	-	-	-	-
09-12	0.90	3,740	14	324	116	0.0087	291.6	0.078	135	155
09-13	0.89	-	-	-	-	-	-	-	-	-

(continued)

TABLE D-3. (continued)

Date	Θ [d]	X [mg VSS/L]	X_e [mg VSS/L]	$Q_wX + Q_eX_e$ [mg VSS/d]	Θ_c [d]	$1/\Theta_c$ [d^{-1}]	R_r[a] [mg O_2/L-d]	R_r/X [mg O_2/mg VSS-d]	ZSV [gpd/ft^2]	SVI [mLs/gm]
09-14	0.92	3,710	12	298	125	0.0080	345.6	0.093	135	161
09-15	0.91	-	-	-	-	-	-	-	-	-
09-16	0.91	3,820	11	293	130	0.0077	419.8	0.110	104	163
09-17	0.92	-	-	-	-	-	-	-	-	-
09-18	0.92	-	-	-	-	-	-	-	-	-
09-19	0.90	-	-	-	-	-	-	-	-	-
09-20	0.92	3,600	7	2,383	151	0.0066	209.5	0.058	104	174
09-21	0.90	3,750	11	290.4	129	0.0077	345.6	0.092	97	169
09-22	0.96	-	-	-	-	-	-	-	-	-
09-23	0.94	3,660	9	261	140	0.0072	345.6	0.094	99	171

[a] Equilibrium demand.

[b] Initial demand.

APPENDIX E

AMMONIA REMOVAL PERFORMANCE DATA

TABLE E-1. BIOREACTOR 1 AMMONIA PERFORMANCE DATA

	Influent, So				Se	1/Se	U	1/U
	Measured	SCN Destroyed	Delta as N	Adjusted			(So - Se)/Xθ	
Date	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[L/mg]	[mg NH_3-N/mg VSS-d]	[mg VSS-d/mg NH_3-N]
08-10	258	-	32[a]	290	<1	1	0.156	6.41
08-11	258	-	32[a]	290	<1	1	0.156	6.41
08-12	258	-	32[a]	290	<1	1	0.156	6.41
08-13	265	-	32[a]	297	<1	1	0.156	6.4
08-14	265	-	32[a]	297	<1	1	0.154	6.48
08-17	255	135	33	288	<1	1	0.134	7.46
08-21	255	123	30	285	<1	1	0.143	6.98
08-24	250	149	36	286	<1	1	0.138	7.25
08-28	250	-	32[a]	282	<1	1	0.157	6.37
08-31	245	145	35	280	<1	1	0.13	7.69
09-05	261	147	35	296	<1	1	0.163	6.13
09-08	238	116	28	266	<1	1	0.140	7.14
09-12	255	134	32	287	<1	1	0.151	6.62
09-14	253	-	32[a]	285	<1	1	0.158	6.31
09-15	250	-	32[a]	282	<1	1	0.145	6.90
09-18	250	126	30.4	280.4	<1	1	0.146	6.87
09-21	248	124	29.9	277.9	<1	1	0.153	6.53

[a] Estimated from the mean of the data set.

TABLE E-2. BIOREACTOR 2 AMMONIA PERFORMANCE DATA

	Influent, So				Se	1/Se	U	1/U
	Measured	SCN Destroyed	Delta as N	Adjusted			(So - Se)/XΘ	
Date	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[L/mg]	[mg NH$_3$-N/mg VSS-d]	[mg VSS-d/mg NH$_3$-N]
08-10	258	-	32[a]	290	<1	1	0.11	9.09
08-11	258	-	32[a]	290	<1	1	0.109	9.16
08-12	258	-	32[a]	290	<1	1	0.108	9.25
08-13	265	-	32[a]	297	<1	1	0.111	9.04
08-14	265	-	32[a]	297	<1	1	0.112	8.94
08-17	255	135	33	288	<1	1	0.105	9.54
08-21	255	123	30	285	<1	1	0.104	9.63
08-24	250	150	36	286	<1	1	0.103	9.71
08-28	250	-	32[a]	282	<1	1	0.104	9.62
08-31	245	145	35	280	<1	1	0.104	9.62
09-05	261[b]	147	35	296	-	-	-	-
09-08	238	116	28	266	<1	1	0.095	10.53
09-12	255	134	32	287	<1	1	0.117	8.55
09-14	253	-	32[a]	285	<1	1	0.113	8.85
09-15	250	-	32[a]	282	-	-	-	-
09-18	250	126	30.4	280.4	<1	-	0.103	9.69
09-21	248	124	29.9	277.9	<1	1	0.112	8.94

[a] Estimated from the mean of the data set.

[b] Average of two sample analyses.

TABLE E-3. BIOREACTOR 3 AMMONIA PERFORMANCE DATA

	Influent, So				Se	1/Se	U	1/U
	Measured	SCN Destroyed	Delta as N	Adjusted			(So - Se)/Xθ	
Date	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[L/mg]	[mg NH_3-N/mg VSS-d]	[mg VSS-d/mg NH_3-N]
08-07	255	135	33	288	<1	1	0.082	12.2
08-21	255	123	30	285	<1	1	0.082	12.2
08-24	250	149	36	286	<1	1	0.087	11.49
08-28	250	-	32[a]	282	<1	1	0.091	11.02
08-31	245	145	35	280	<1	1	0.080	12.5
09-05	261[b]	147	35	296	<1	1	0.093	10.75
09-08	238	116	28	266	<1	1	0.078	12.82
09-12	255	134	32	287	<1	1	0.085	11.76
09-14	253	-	32[a]	285	<1	1	0.085	11.76
09-18	250	126	30.4	280.4	<1	1	0.080	12.45
09-21	248	124	29.9	277.9	<1	1	0.082	12.19

[a] Estimated from the mean of the data set.

[b] Average of two sample analyses.

APPENDIX F

CHEMICAL OXYGEN DEMAND AND THIOCYANATE REMOVAL PERFORMANCE DATA

TABLE F-1. BIOREACTOR 1 COD/SCN PERFORMANCE DATA

	Influent, So		Effluent, Se			U	1/U	U	1/U
	COD	SCN	COD	SCN	1/Se	(So - Se)/Xθ			
Date	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[L/mg]	[mg SCN/mg VSS-d]	[mg VSS-d/mg SCN]	[mg COD/mg VSS-day]	[mg VSS-day/mg COD]
08-14	223	134	17	<1	1	0.066	15.09	0.103	9.743
08-17	239	136	<10	<1	1	0.063	15.87	0.107	9.341
08-21	196	124	<10	<1	1	0.062	16.10	0.067	14.832
08-24	212	150	23	<1	1	0.060	16.7	0.092	10.905
08-28	208	127	18	<1	1	0.065	15.33	0.098	10.168
08-31	196	146	17	<1	1	0.068	14.7	0.084	11.95
09-05	145	148	21	<1	1	0.081	12.3	0.068	14.619
09-07	152	-	-	-	-	-	-	-	-
09-08	158	117	12	<1	1	0.059	17.08	0.075	13.249
09-12	152	135	31	<1	1	0.071	14.1	0.064	15.643
09-14	168	138	30	<1	1	0.076	13.09	0.077	12.991
09-18	162	127	11	<1	1	0.064	15.7	0.085	11.825
09-21	172	125	9	<1	1	0.068	14.7	0.090	11.119

TABLE F-2. BIOREACTOR 2 COD/SCN PERFORMANCE DATA

	Influent, So		Effluent, Se			U	1/U	U	1/U
	COD	SCN	COD	SCN	1/Se	(So - Se)/Xθ			
Date	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[L/mg]	[mg SCN/mg VSS-d]	[mg VSS-d/mg SCN]	[mg COD/mg VSS-day]	[mg VSS-day/mg COD]
08-14	223	134	<10	<1	1	0.051	19.69	0.081	12.30
08-17	239	136	10	<1	1	0.049	20.4	0.083	11.98
08-21	196	124	<10	<1	1	0.045	22.2	0.059	16.85
08-24	212	150	23	<1	1	0.054	18.5	0.069	14.60
08-28	208	127	12	<1	1	0.048	20.75	0.075	13.34
08-31	196	146	16	<1	1	0.054	18.5	0.067	14.96
09-05	145	148	25	<1	1	0.058	17.2	0.048	20.95
09-08	158	117	12	<1	1	0.043	23.1	0.058	17.27
09-12	152	135	30	<1	1	0.055	18.2	0.050	20.07
09-14	168	138	18	<1	1	0.055	18.33	0.06	16.74
09-18	162	127	11	<1	1	0.047	21.5	0.059	16.88
09-21	172	125	26	<1	1	0.05	20.0	0.059	16.95

TABLE F-3. BIOREACTOR 3 COD/SCN PERFORMANCE DATA

	Influent, So		Effluent, Se			U	1/U	U	1/U
	COD	SCN	COD	SCN	1/Se	(So - Se)/Xθ			
Date	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[L/mg]	[mg SCN/mg VSS-d]	[mg VSS-d/mg SCN]	[mg COD/mg VSS-day]	[mg VSS-day/mg COD]
08-14	223	134	49	<1	1	0.040	24.75	0.053	18.92
08-17	239	136	20	<1	1	0.038	26.31	0.063	15.99
08-21	196	124	<10	<1	1	0.035	28.6	0.057	17.52
08-24	212	150	16	<1	1	0.045	22.22	0.060	16.73
08-28	208	127	15	<1	1	0.041	24.67	0.062	16.10
08-31	196	146	22	<1	1	0.042	23.81	0.050	20.02
09-05	145	148	25	<1	1	0.046	21.74	0.038	26.54
09-08	158	117	19	<1	1	0.034	29.4	0.041	24.60
09-12	152	135	11	<1	1	0.0398	25.12	0.042	23.87
09-14	168	138	<10	<1	1	0.040	24.91	0.046	21.60
09-18	162	127	12	<1	1	0.036	27.56	0.043	23.43
09-21	172	125	11	<1	1	0.037	27.22	0.048	20.96

APPENDIX G

TOTAL ORGANIC CARBON AND BIOCHEMICAL OXYGEN DEMAND REMOVAL PERFORMANCE DATA

TABLE G-1. BIOREACTOR 1 TOC/BOD PERFORMANCE DATA

	Influent, So			Effluent, Se		1/Se	U	1/U
	TOC	BOD		TOC	BOD		(So - Se)/Xθ	
		Total	Soluble		Total			
Date	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[L/mg]	[mg BOD/mg VSS-d]	[mg VSS-d/mg BOD]
08-14	40	1,137	-	<2	3.7	0.27	0.565	1.77
08-17	40	1,175[a]	-	3	5.6[b]	0.18	0.547	1.83
08-21	39	1,163[a]	-	<2	3.7[b]	0.27	0.674	1.48
08-24	42	1,167[a]	-	4	7.5[b]	0.13	0.563	1.78
08-28	36	1,151[a]	-	3	5.6[b]	0.18	0.593	1.69
08-31	33	1,142[a]	-	2	7.2[b]	0.14	0.531	1.89
09-05	29	1,207	-	4	3.7	0.27	0.664	1.51
09-08	29	1,208[a]	-	3	5.6[b]	0.18	0.635	1.57
09-09	35	1,085	-	-	-	-	-	-
09-12	31	1,171[a]	-	3	5.6[b]	0.18	0.616	1.624
09-14	33	1,539	-	4	7.5	0.13	0.854	1.17
09-18	42	1,144[a]	-	3	6.1[b]	0.16	0.631	1.59
09-21	42	1,013	968	3	5.6	0.18	0.556	1.80

[a] Estimated from BOD_{20}/NH_3-N.

[b] Estimated from BOD_{20}/TOC.

TABLE G-2. BIOREACTOR 2 TOC/BOD PERFORMANCE DATA

	Influent, So			Effluent, Se		1/Se	U	1/U
	TOC	BOD		TOC	BOD		(So - Se)/Xθ	
		Total	Soluble		Total			
Date	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[L/mg]	[mg BOD/mg VSS-d]	[mg VSS-d/mg BOD]
08-14	40	1,137	-	<2	3.7	0.27	0.433	2.31
08-17	40	1,175[a]	-	<2	3.7[b]	0.27	0.427	2.34
08-21	39	1,163[a]	-	<2	3.7[b]	0.27	0.370	2.70
08-24	42	1,167[a]	-	4	7.5[b]	0.13	0.42	2.38
08-28	36	1,151[a]	-	<2	3.7[b]	0.27	0.428	2.33
08-31	33	1,142[a]	-	2	3.7[b]	0.27	0.423	2.37
09-05	29	1,207	-	4	7.5	0.13	0.477	2.10
09-08	29	1,208[a]	-	3	5.6[b]	0.18	0.482	2.07
09-09	35	1,085[a]	-	-	-	-	-	-
09-12	31	1,171[a]	-	3	5.6[b]	0.18	0.476	2.10
09-14	33	1,539	-	3	5.6	0.18	0.613	1.63
09-18	42	1,144[a]	-	3	5.6[b]	0.18	0.448	2.23
09-21	42	1,013	968	3	5.6	0.18	0.407	2.46

[a] Estimated from BOD_{20}/NH_3-N.

[b] Estimated from BOD_{20}/TOC.

TABLE G-3. BIOREACTOR 3 TOC/BOD PERFORMANCE DATA

	Influent, So			Effluent, Se		1/Se	U	1/U
	TOC	BOD		TOC	BOD		(So - Se)/XΘ	
		Total	Soluble		Total			
Date	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[L/mg]	[mg BOD/mg VSS-d]	[mg VSS-d/mg BOD]
08-14	40	1,137	-	<2	3.7	0.27	0.344	2.90
08-17	40	1,175[a]	-	3	5.6[b]	0.18	0.334	2.99
08-21	39	1,163[a]	-	<2	3.7[b]	0.27	0.326	3.06
08-24	42	1,167[a]	-	2	3.7[b]	0.27	0.355	2.82
08-28	36	1,151[a]	-	2	3.7[b]	0.27	0.363	2.75
08-31	33	1,142[a]	-	2	3.7[b]	0.27	0.327	3.06
09-05	29	1,207	-	3	5.6	0.18	0.377	2.65
09-08	29	1,208[a]	-	4	7.5[b]	0.13	0.346	2.89
09-09	35	1,085[a]	-	-	-	-	-	-
09-12	31	1,171[a]	-	3	5.6[b]	0.18	0.346	2.89
09-14	33	1,539	-	3	5.6	0.18	0.449	2.23
09-18	42	1,144[a]	-	3	5.6[b]	0.18	0.334	3.0
09-21	42	1,013	968	3	5.6	0.18	0.298	3.35

[a] Estimated from BOD_{20}/NH_3-N.

[b] Estimated from BOD_{20}/TOC.

APPENDIX H

SUBSTRATE REMOVAL DATA STATISTICS

TABLE H-1. DATA STATISTICS

PARAMETER: SCN

	$1/\theta_c$ $[\text{days}]^{-1}$			U $[\frac{\text{mg substrate}}{\text{mg VSS-day}}]$			1/U $[\frac{\text{mg VSS-day}}{\text{mg substrate}}]$			1/Se $[\frac{\text{L}}{\text{mg substrate}}]$		
Reactor	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**	**N**
1	0.017	0.002	19	0.067	0.006	12	15.1	1.4	12	1.0	0	12
2	0.010	0.0014	19	0.051	0.005	12	19.9	1.8	12	1.0	0	12
3	0.007	0.001	19	0.039	0.004	12	25.5	2.4	12	1.0	0	12

PARAMETER: NH_3

	$1/\theta_c$ $[\text{days}]^{-1}$			U $[\frac{\text{mg substrate}}{\text{mg VSS-day}}]$			1/U $[\frac{\text{mg VSS-day}}{\text{mg substrate}}]$			1/Se $[\frac{\text{L}}{\text{mg substrate}}]$		
Reactor	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**	**N**	**Mean**	**Std. Dev.**	**N**
1	0.017	0.002	19	0.149	0.009	17	6.73	0.45	17	1.0	0	16
2	0.010	0.014	19	0.107	0.005	15	9.34	0.49	15	1.0	0	15
3	0.007	0.001	19	0.084	0.005	11	11.92	0.64	11	1.0	0	11

(continued)

TABLE H-1. (continued)

PARAMETER: COD

	$1/\theta_c$ $[\text{days}]^{-1}$			U $\left[\frac{\text{mg substrate}}{\text{mg VSS-day}}\right]$			1/U $\left[\frac{\text{mg VSS-day}}{\text{mg substrate}}\right]$			1/Se $\left[\frac{\text{L}}{\text{mg substrate}}\right]$		
Reactor	Mean	Std. Dev.	N	Mean	Std. Dev.	N	Mean	Std. Dev.	N	Mean	Std. Dev.	N
1	0.017	0.002	19	0.084	0.014	12	12.2	2.1	12	0.068	0.028	12
2	0.010	0.0014	19	0.064	0.011	12	16.1	2.8	12	0.069	0.026	12
3	0.007	0.001	19	0.05	0.009	12	20.5	3.6	12	0.067	0.026	12

PARAMETER: TOC

	$1/\theta_c$ $[\text{days}]^{-1}$			U $\left[\frac{\text{mg substrate}}{\text{mg VSS-day}}\right]$			1/U $\left[\frac{\text{mg VSS-day}}{\text{mg substrate}}\right]$			1/Se $\left[\frac{\text{L}}{\text{mg substrate}}\right]$		
Reactor	Mean	Std. Dev.	N	Mean	Std. Dev.	N	Mean	Std. Dev.	N	Mean	Std. Dev.	N
1	0.017	0.002	19	0.017	0.003	12	59.0	10.2	12	0.354	0.095	12
2	0.010	0.0014	19	0.013	0.002	12	80.3	12.5	12	0.389	0.103	12
3	0.007	0.001	19	0.01	0.002	12	102.6	17.8	12	0.396	0.045	12

(continued)

TABLE H-1. (continued)

PARAMETER: BOD_{20}

	$1/\theta_c$ $[\text{days}]^{-1}$			U $[\frac{\text{mg substrate}}{\text{mg VSS-day}}]$			1/U $[\frac{\text{mg VSS-day}}{\text{mg substrate}}]$			1/Se $[\frac{\text{L}}{\text{mg substrate}}]$		
Reactor	Mean	Std. Dev.	N	Mean	Std. Dev.	N	Mean	Std. Dev.	N	Mean	Std. Dev.	N
1	0.017	0.002	19	0.619	0.088	12	1.64	0.20	12	0.19	0.05	12
2	0.01	0.0014	19	0.45	0.06	12	2.25	0.26	12	0.21	0.06	12
3	0.007	0.001	19	0.35	0.037	12	2.88	0.27	12	0.21	0.05	12

APPENDIX I

BIOOXIDATION TEMPERATURE IMPACT ANALYSIS

TABLE I-1. TEMPERATURE IMPACT ANALYSIS

Temperature (°C)	Influent		Effluent				Substrate Utilization	
	NH_3-N (mg/L)	SCN (mg/L)	NH_3-N (mg/L)	SCN (mg/L)	MLVSS (mg/L)	Sludge Age (days)	NH_3-N	SCN
							$\left(\frac{\text{mg Substrate}}{\text{mg VSS-day}}\right)$	
17.9 ± 0.2	275	129	0.15	1.3	3,540	119	0.083	0.038
	283	139	0.13	<1	3,490	142	0.088	0.043
	292	144	0.05	<1	3,700	185	0.087	0.042
	289	131	<0.05	<1	3,465	149	0.093	0.042
	280	126	0.09	<1	3,600	152	0.084	0.037
	289	129	0.25	<1	3,610	153	0.083	0.037
14.9 ± 0.2	288	126	0.07	<1	3,600	158	0.088	0.038
	286	118	0.05	<1	3,620	159	0.085	0.035
	277	124	0.08	1.1	3,580	146	0.081	0.036

(continued)

TABLE I-1. (continued)

Temperature (°C)	Influent		Effluent		MLVSS	Sludge Age	Substrate Utilization	
	NH_3-N (mg/L)	SCN (mg/L)	NH_3-N (mg/L)	SCN (mg/L)	(mg/L)	(days)	NH_3-N ($\frac{\text{mg Substrate}}{\text{mg VSS-day}}$)	SCN
11.5 ± 0.7	279	121	0.17	1.1	3,600	135	0.082	0.035
	278	116	<0.05	1.0	3,670	113	0.081	0.034
	283	126	<0.05	1.2	3,650	109	0.082	0.036
	277	121	<0.05	1.2	3,600	96	0.082	0.035
9.4 ± 0.4	280	128	25	1.3	3,590	100	0.073	0.036
	282	133	150	<1	3,590	102	0.037	0.037
	279	123	233	<1	3,540	101	0.013	0.035
	282	133	240	<1	3,495	100	0.012	0.038
	279	123	258	<1	3,400	112	0.006	0.036
	279	124	265	1.6	3,360	128	0.004	0.037

(continued)

TABLE I-1. (continued)

Temperature (^{o}C)	Influent NH_3-N (mg/L)	Influent SCN (mg/L)	Effluent NH_3-N (mg/L)	Effluent SCN (mg/L)	MLVSS (mg/L)	Sludge Age (days)	Substrate Utilization NH_3-N ($\frac{\text{mg Substrate}}{\text{mg VSS-day}}$)	Substrate Utilization SCN ($\frac{\text{mg Substrate}}{\text{mg VSS-day}}$)
8.0 ± 0.3	279	123	252	1.1	2,820	119	0.010	0.043
	278	118	252	<1	2,670	106	0.010	0.045
5.6 ± 1.2	283	118	260	<1	2,550	110	0.009	0.045
	273	118	270	1.6	2,550	109	0.001	0.045
	286	133	270	1.9	2,505	92	0.007	0.055
	282	133	295	20	2,900	114	-	0.039
	277	132	294	30	2,960	153	-	0.035

APPENDIX J

BIOOXIDATION NONSUBSTRATE ION IMPACT ANALYSIS

TABLE J-1. BIOOXIDATION NONSUBSTRATE ION TOXICITY TEST -- CONTROL BIOREACTOR[a]

Influent		Effluent		MLVSS	Sludge Age	Substrate Utilization	
NH_3-N (mg/L)	SCN (mg/L)	NH_3-N (mg/L)	SCN (mg/L)	(mg/L)	(day)	NH_3-N $\left(\frac{\text{mg Substrate}}{\text{mg VSS-day}}\right)$	SCN
280	128	<1	<1	2,060	119	0.137	0.062
282	133	<1	<1	2,060	NA[b]	0.144	0.067
279	123	<1	<1	2,090	NA[b]	0.125	0.055
280	124	<1	<1	3,000	NA[b]	0.095	0.042
281	132	<1	<1	3,040	161	0.097	0.045
281	132	<1	<1	3,040	170	0.096	0.045
279	123	<1	<1	2,920	169	0.099	0.044
278	118	<1	<1	2,720	155	0.107	0.045
283	118	<1	<1	2,660	167	0.106	0.044
275	133	<1	<1	2,910	161	0.095	0.046
283	132	<1	<1	2,940	138	0.097	0.045
301	130	<1	<1	2,910	169	0.107	0.046
299	130	<1	<1	2,920	138	0.103	0.045
300	130	<1	<1	2,890	160	0.105	0.045

a	Temperature	(°C)	20.5 ± 0.9
a	MLSS	(mg/L)	3,672 ± 429
a	pH	(S.U.)	7.0 ± 0.05
a	TDS	(mg/L)	2,872 ± 185
a	Chloride	(mg/L)	499
a	Fluoride	(mg/L)	17
a	Boron	(mg/L)	9.7

b Data not available.

TABLE J-2. BIOOXIDATION NONSUBSTRATE ION TOXICITY TEST -- STRESS BIOREACTOR[a]

Influent		Effluent				Substrate Utilization	
NH_3-N (mg/L)	SCN (mg/L)	NH_3-N (mg/L)	SCN (mg/L)	MLVSS (mg/L)	Sludge Age (day)	NH_3-N ($\frac{\text{mg Substrate}}{\text{mg VSS-day}}$)	SCN
280	128	<1	<1	2,040	124	0.142	0.065
282	133	<1	<1	2,430	NA[b]	0.120	0.057
279	123	<1	<1	2,630	NA[b]	0.109	0.048
280	124	<1	<1	2,825	NA[b]	0.105	0.046
279	123	<1	<1	3,010	169	0.098	0.043
281	131	<1	<1	3,020	158	0.103	0.048
280	126	<1	<1	2,980	170	0.098	0.044
278	118	<1	<1	3,000	152	0.096	0.041
283	118	<1	<1	2,930	153	0.095	0.040
275	133	<1	<1	2,620	138	0.109	0.052
283	132	<1	<1	3,570	118	0.081	0.037
301	130	<1	<1	3,250	NA[b]	0.096	0.041
301	130	<1	<1	3,215	95	0.10	0.043
299	130	<1	<1	3,090	129	0.097	0.047
300	130	<1	<1	3,080	140	0.098	0.042

---

[a]	Temperature	(°C)	20.8 ± 1.1
[a]	MLSS	(mg/L)	8,341 ± 1,319
[a]	pH	(S.U.)	6.95 ± 0.05
[a]	TDS	(mg/L)	7,286 ± 873
[a]	Chloride	(mg/L)	3,087 ± 157
[a]	Fluoride	(mg/L)	275 ± 23
[a]	Boron	(mg/L)	146 ± 6

[b] Data not available.

TABLE J-3. ANIONS PRESENT IN BIOTREATED WASTEWATERS DURING NONSUBSTRATE ION IMPACT TESTING

Date	Reactor	Chloride (mg/L)		Boron (mg/L)		Fluoride (mg/L)	
		Influent	Effluent	Influent	Effluent	Influent	Effluent
11-03-83	Stress	3,278	--	--	--	--	--
11-05-83	Stress	3,316	--	148	135	--	--
11-08-83	Stress	--	--	--	--	261	--
11-09-83	Stress	--	--	150	145	287	260
11-11-83	Stress	--	--	--	--	285	285
11-12-83	Stress	--	--	151	140	--	--
11-14-83	Stress	3,253	3,210	148	150	296	273
11-17-83	Stress	--	--	150	150	290	305
11-22-83	Stress	3,084	3,235	146	150	290	235
11-25-83	Stress	3,033	2,958	150	150	300	285
11-28-83	Stress	2,995	2,945	147	150	290	285
11-09-83	Control	--	--	--	--	12.9	--
11-14-83	Control	445	--	--	--	12.3	12.4

APPENDIX K

BIOCHEMICAL OXYGEN DEMAND RELATIONSHIPS

TABLE K-1. RELATIONSHIP BETWEEN INFLUENT BOD_{20} AND OTHER POLLUTANT PARAMETERS IN KRW WASTEWATER

BOD_{20} (mg/L)	TOC (mg/L)	COD (mg/L)	NH_3-N (mg/L)	SCN (mg/L)	BOD_{20}/TOC	BOD_{20}/COD	BOD_{20}/NH_3-N	BOD_{20}/SCN
1,137	40	223	297	134	28.43	5.10	3.83	8.49
1,207	29	145	296	148	41.62	8.32	4.08	8.16
1,539	33	168	285	138	46.64	9.16	5.40	11.15
1,013	42	172	278	125	24.12	5.89	3.64	8.10
1,013	39	167	292	144	25.97	6.07	3.47	7.03
Mean					33.36	6.91	4.08	8.59
Standard Deviation					10.11	1.74	0.77	1.53
Variance					0.3	0.25	0.19	0.18

TABLE K-2. RELATIONSHIP BETWEEN EFFLUENT BOD$_{20}$ AND OTHER POLLUTANT PARAMETERS IN BIOREACTOR EFFLUENT

BIOREACTOR 1

BOD$_{20}$ (mg/L)	COD (mg/L)	TOC (mg/L)	NH_3-N (mg/L)	SCN (mg/L)
7.15	17	2	<1	<1
3.70	21	4	<1	<1
-	-	-	-	-
6.05	11	3	<1	<1
	BOD$_{20}$/COD	BOD$_{20}$/TOC		
-	0.42	3.58	-	-
-	0.18	0.93	-	-
-	-	-	-	-
-	0.55	2.02	-	-

(continued)

TABLE K-2. (continued)

BIOREACTOR 2

BOD_{20} (mg/L)	COD (mg/L)	TOC (mg/L)	NH_3-N (mg/L)	SCN (mg/L)
2.59	16	2	<1	<1
3.80	25	4	<1	<1
5.90	18	3	<1	<1
6.65	11	3	<1	<1
	BOD_{20}/COD	BOD_{20}/TOC		
-	0.16	1.3	-	-
-	0.15	0.95	-	-
-	0.33	1.97	-	-
-	0.60	2.22	-	-

(continued)

TABLE K-2. (continued)

BIOREACTOR 3

BOD_{20} (mg/L)	COD (mg/L)	TOC (mg/L)	NH_3-N (mg/L)	SCN (mg/L)
4.20	22	2	<1	<1
3.05	25	3	<1	<1
5.55	10	3	<1	<1
7.95	12	3	<1	<1
	BOD_{20}/COD	BOD_{20}/TOC		
-	0.19	2.1	-	-
-	0.12	1.02	-	-
-	0.56	1.85	-	-
-	0.66	2.65	-	-
Mean of all data	0.36	1.87		
Standard Deviation	0.21	0.81		
Variance	0.59	0.43		

APPENDIX L

SAMPLE HANDLING AND ANALYSIS PROCEDURES INCLUDING ANALYTICAL QUALITY ASSURANCE/QUALITY CONTROL

The analytical methods which were employed during the study are indicated in Table L-1. Also shown are the means of sample preservation and the actual sample holding time versus the recommended limit for sample storage. Generally, effluent samples were collected over a 24-hour period. Occasionally, samples also were collected directly from the settling chambers of the test bioreactors as a check on treatment performance. Influent samples were collected at the same time as effluent samples. Analysis of the feed at the time of preparation and when feed samples were collected for performance testing indicated no apparent degradation in sample quality over the 24 hours that the feed would sit before sample collection. All liquid samples were filtered through a Buchner funnel utilizing Whatman #42 filters. These samples were then filtered again through a Millipore filter apparatus utilizing Whatman Glass Fibre 0.45 micron filters.

Samples for routine analyses were collected in detergent washed and distilled water rinsed Nalgene containers. All samples which were not analyzed immediately (within 10 minutes of collection) were preserved according to EPA guidelines (EPA-600/4-79-020) for the parameter of interest and stored at 4°C until analysis could begin.

Bioreactor operation and effluent quality parameters examined during the treatability study are indicated in the analytical schedule shown in Table L-2. This schedule was maintained rigorously throughout the steady-state operating period.

TABLE L-1. ANALYTICAL METHODS FOR TREATABILITY ANALYSIS

Parameter	Analytical Method Reference	Method Description	Preservation[a] Technique	Actual Sample Holding Time/Recommended Maximum Holding Time
Total organic carbon	EPA 415.1 / SM 505	Nonpurgeable combustion, NDIR (Beckman 915A)	HCl or H_2SO_4, pH<1	< 3 hr/ 7 da [b]
Biochemical oxygen demand	EPA 405.1 / SM 507, 421B	Incubation, 20°C titration	—	< 2 hr
Chemical oxygen demand	EPA 410 / SM 508	Dichromate reflux titration	H_2SO_4, pH<2	< 3 hr/ 5 da
Ammonia nitrogen	EPA 350.3 / SM 417E	Specific ion electrode	H_2SO_4, pH<2	< 1 hr
	EPA 350.1 / SM 417F	Automated phenolate	H_2SO_4, pH2<2	<24 hr/ 5 da
Total Kjeldahl nitrogen	EPA 351.3 / SM 420A, 417D	Digestion, titration	H_2SO_4, pH<2	< 6 hr/14 da
Organic nitrogen	/ SM 420A, 417D	NH_3 removal, digestion, titration	H_2SO_4, pH<2	< 6 hr/ 3 da
Nitrate-nitrogen	EPA 353.1 /	Automated hydrazine reduction	H_2SO_4, pH<2	< 6 hr/ 5 da [c]
Nitrite nitrogen	EPA 353.1 /	Automated hydrazine reduction	H_2SO_4, pH<2	< 6 hr/ 5 da [c]
Thiocyanate	/ SM 421K	Colorimetry	NaOH, pH>12	24 hr/<14 da
Total cyanide	EPA 335.2 /	Distillation, colorimetry	NaOH, pH>12	24 hr/<14 da
Total alkalinity	EPA 310.1 / SM 403	Potentiometric titration	—	<24 hr
Total suspended solids	EPA 160.3 / SM 209D	Gravimetry, 103°C	—	NHT[d]
Volatile suspended solids	EPA 160.4 / SM 209E	Gravimetry, 550°C	—	NHT[d]
Total dissolved solids	EPA 160.1 / SM 209B	Gravimetry, 180°C filtered	—	< 3 hr/ 5 da
Total phosphorus	EPA 365.2 / SM 424CIII, 424F	Persulfate, digestion, colorimetry	H_2SO_4, pH<2	<12 hr/14 da
Chloride	EPA 325.3 / SM 407A, 407C	Titration, potentiometry	—	<12 hr/ 3 da
Boron	/ SM 404B	Colorimetry	—	24 hr/ 8 da
Fluoride	EPA 340.2 / SM 413B, 413A	Specific ion electrode	—	< 1 hr/ 3 da
Hydrogen ion concentration	EPA 150.1 / SM 423	Potentiometry	—	NHT[d]
Oxygen uptake	/ SM 213A	Membrane electrode (10 min.)	—	NHT[d]
Settleability	/ SM 213B, C, D	Visual, no stirring (30 min.)	—	NHT[d]

(continued)

TABLE L-1. NOTES

[a] Samples not analyzed immediately were stored at 4°C.

[b] Actual sample holding time during treatability study/recommended maximum holding time.

[c] NO_3/NO_2: majority of samples analyzed within 24 hours after collection.

[d] No recommended holding time; therefore, analyses were conducted immediately upon collection of sample.

Sources

EPA	Methods for Chemical Analysis of Water and Wastes, EPA-600/4-79-020, 3/79.
SM	Standard Methods for the Examination of Water and Wastewater, APHA-AWWA-WPCF, 15th ed., 1980.

TABLE L-2. TESTING FREQUENCY DURING STEADY-STATE BIOREACTOR OPERATION

Parameter per Bioreactor	08/13/83		08/20/83		08/27/83		09/03/83		09/10/83		09/17/83	
	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.
Performance Parameters[a]												
BOD (mg/L)	1[b]	1	-	-	1	1	1	1	1	1	2[c]	3[c]
TOC (mg/L)	2	2	2	2	2	2	3	2	2	2	2	2
COD (mg/L)	2	2	2	2	2	2	3	2	2	2	2	2
NH_3-N (mg/L)	3	3	3	2	3	2	3	2	3	2	2	2
NO_3-N (mg/L)	2	2	2	2	2	2	2	2	3	2	2	2
NO_2-N (mg/L)	2	2	2	2	2	2	2	2	3	2	2	2
Thiocyanate (mg/L)	2	2	2	2	2	2	2	2	2	2	2	2
Total cyanide (mg/L)	2	2	2	2	2	2	2	2	2	2	2	2
Total PO_4 (mg/L-P)	1	1	1	1	2	2	1	1	0	0	1	1
TSS (mg/L)	2	2	3	3	4	4	3	3	3	3	3	3
VSS (mg/L)	2	2	3	3	4	4	3	3	3	3	3	3
TDS (mg/L)	2	2	2	2	2	2	2	2	2	2	2	2
Total Alkalinity (mg/L-$CaCO_3$)	2	2	2	2	2	2	3	2	2	2	2	2
pH	10	7	8	7	8	7	9	7	10	7	9	7
Operational Parameters												
Flow rate (L/day)	7		7		7		7		7		7	
Caustic rate (mL/day)	7		7		7		7		7		7	
MLSS (mg/L)	2		3		4		3		3		3	
MLVSS (mg/L)	2		3		4		3		3		3	
pH[d]	8 + ct		9 + ct		7 + ct		8 + ct		8 + ct		9 + ct	
Temperature (°C)	7		7		7		6		7		7	
D.O.[e] (mg/L)	2		3		4		3		3		3	
O.U.R.[f] (mg/L-hr)	2		3		4		3		3		3	
ZSV (m/hr)	2		3		4		3		3		3	
Settleability (mL/30 min)	2		3		4		3		3		3	
Solids wasted (mL/day)	7		7		7		7		7		7	

[a] Analyses performed on filtered samples with the following exceptions: BOD (filtered and unfiltered), TSS, VSS, pH.

[b] Number of analyses per week per bioreactor.

[c] Steady-state includes data for week of 09/24/83 on a single bioreactor that was used as a control in later testing.

[d] pH: meter readings per week plus continuous recordings on pH controller (ct).

[e] Dissolved oxygen.

[f] Oxygen uptake rate.

Twice during steady-state operation, influent and effluent samples were collected from one of the test bioreactors. The samples were obtained for analysis of toxic organics and trace elements. Aliquots of each sample were collected every three hours until the required volume was collected and placed in containers to which the appropriate preservatives were added. Glass containers were used to hold the feed and effluent samples until the sample volumes could be transferred to the storage containers. Preservation techniques are summarized in Figure L-1.

EPA quality control samples were analyzed for COD, TOC, and nitrate in October 1983. The results of this test are presented in Table L-3.

Samples not analyzed the day of collection were analyzed within the allowable holding time period established by EPA (see Table L-1) for the parameter of concern. Test samples also were analyzed over a period of time extending past the normal sample holding times established by EPA in order to test whether a deviation from established holding times might effect analytical accuracy. These data are presented in Table L-4. The change in pollutant concentration with storage time for a randomly selected sampling of the data set is summarized in this table. In general, these data show no major sample quality changes with holding time except for a NO_3-N sample (B3E 8-14) which indicates a 10 percent increase in pollutant concentration over a 7 day storage period. This may have been due to continued nitrification during sample storage, apparently because this particular sample was not acidified before refrigeration. When samples for NO_3-N analysis were stored according to proper EPA guidelines no major deviations in sample quality were noticed.

At least 10 percent of all data collected for most parameters were analyzed in duplicate. In addition, replicates of samples occasionally were tested for most parameters. A randomly selected sampling of the duplicate/replicate analyses is presented in Table L-5 for the parameters alkalinity, TOC, NH_3, NO_3, NO_2, and TDS. Duplicate analytical results for residue (TSS and VSS) analyses are presented in Table L-6.

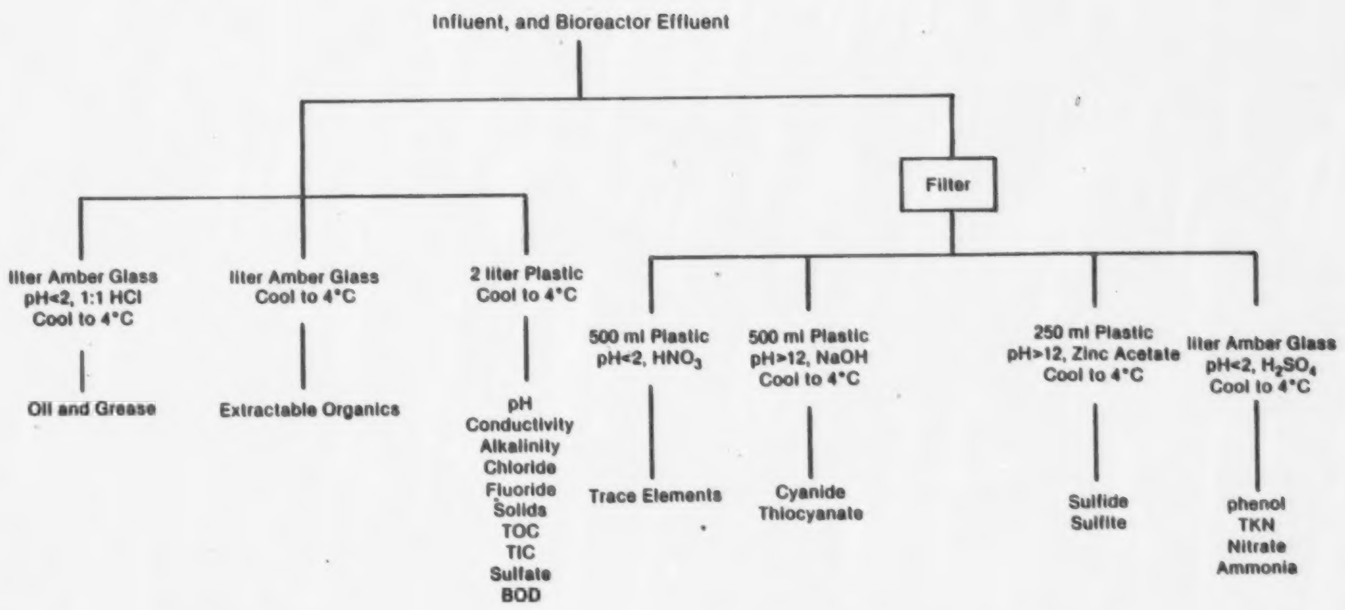
Influent, and Bioreactor Effluent
Filter
liter Amber Glass
pH<2, 1:1 HCl
Cool to 4°C
Oil and Grease
liter Amber Glass
Cool to 4°C
Extractable Organics
2 liter Plastic
Cool to 4°C
pH
Conductivity
Alkalinity
Chloride
Fluoride
Solids
TOC
TIC
Sulfate
BOD
500 ml Plastic
pH<2, HNO3
Trace Elements
500 ml Plastic
pH>12, NaOH
Cool to 4°C
Cyanide
Thiocyanate
250 ml Plastic
pH>12, Zinc Acetate
Cool to 4°C
Sulfide
Sulfite
liter Amber Glass
pH<2, H2SO4
Cool to 4°C
phenol
TKN
Nitrate
Ammonia

Figure L-1. Sample handling protocol for wastewater characterization analysis

TABLE L-3. RESULTS OF EPA QUALITY CONTROL SAMPLE ANALYSIS

Parameter	EPA True Value (mg/L)	EPA 95 Percent Confidence Interval (mg/L)	Reported Value (mg/L)
Total Organic Carbon	91.8	74.6 - 107	92
Chemical Oxygen Demand	233.8	190 - 258	220
Nitrate-Nitrogen	1.32	-	1.35

TABLE L-4. CHANGE IN CONCENTRATION DURING EXTENDED STORAGE TIME

Sample Identification	$NO_3 + NO_2$		NO_2		TOC		Total PO_4		Total Alkalinity		COD	
	Storage Time (d)[a]	Conc. (mg/L-N)	Storage Time (d)[a]	Conc. (mg/L-N)	Storage Time (d)[a]	Conc. (mg/L-C)	Storage Time (d)[a]	Conc. (mg/L-P)	Storage Time (d)[a]	Conc. (mg/L-$CaCO_3$)	Storage Time (d)[a]	Conc. (mg/L)
I123 08-14	-	-	7	0.0	9	+4	21	0.0	-	-	-	-
B1E 08-14	7	-7	7	0.0	27	<+1	21	0.0	-	-	-	-
B2E 08-14	7	+8[b]	7	-0.02	27	<+1	21	0.0	-	-	-	-
B3E 08-14	7	+27	7	0	27	<+1	21	0.0	-	-	-	-
I123 08-17	19	0	19	<+0.10	-	-	-	-	-	-	-	-
B1E 08-17	19	+10	16	+0.01	-	-	-	-	-	-	-	-
B2E 08-17	19	+6	16	0	-	-	-	-	-	-	-	-
B3E 08-17	19	+12	16	0	-	-	-	-	-	-	-	-
I123 08-21	15	+0.25	15	0	-	-	-	-	-	-	17	-3
B1E 08-21	15	-9	12	0	-	-	-	-	-	-	-	-
B2E 08-21	15	+3	12	0	-	-	-	-	-	-	-	-
B3E 08-21	15	+4	12	0	-	-	-	-	-	-	-	-
B1E 08-24	3	+15	3	0	-	-	-	-	15	-3	-	-
B2E 08-24	3	-10	3	0	-	-	-	-	15	+2	-	-
B3E 08-24	3	0	3	0	-	-	-	-	15	+2	-	-
I123 08-28	-	-	3	+0.01	-	-	-	-	4	0	-	-
B1E 08-28	3	+5	3	0	-	-	-	-	4	-1	-	-
B2E 08-28	3	-20	3	0	-	-	-	-	4	0	-	-
B3E 08-28	3	+10	3	0	-	-	-	-	4	+1	-	-
I123 08-31	-	-	3	0	8	0	-	-	-	-	-	-
I123 09-05	7	+0.2	7	0	-	-	-	-	-	-	-	-
B2E 09-05	7	+1	7	<+0.10	-	-	-	-	-	-	-	-
I123 09-08	-	-	-	-	-	-	7	0	-	-	-	-
B1E 09-08	-	-	-	-	-	-	7	0	-	-	-	-
B2E 09-08	-	-	-	-	-	-	7	0	-	-	-	-
B3E 09-08	-	-	-	-	-	-	7	0	-	-	-	-
I123 09-21	5	0	-	-	-	-	-	-	-	-	-	-
B1E 09-21	5	-5	-	-	-	-	-	-	-	-	-	-
B2E 09-21	5	0	-	-	-	-	-	-	-	-	-	-
B3E 09-21	5	-5	-	-	-	-	-	-	-	-	-	-
I3 10-06	-	-	-	-	16	-1	-	-	-	-	-	-
B3E 10-06	-	-	-	-	7	-0.1	-	-	-	-	-	-
B1E 11-17	-	-	-	-	12	0	-	-	-	-	-	-

[a] Storage time is measured in days.

[b] Value outside of statistical limits of analysis because of improper sample preparation for storage. However, actual deviation was within 10 percent of the initial value of 280 mg/L.

TABLE L-5. LABORATORY QUALITY CONTROL FOR RANDOMLY SELECTED DUPLICATE/REPLICATE SAMPLES

Sample Identification	Total Alkalinity (mg/L-$CaCO_3$)	TOC (mg/L-C)	NH_3 (mg/L-N)	NO_3 (mg/L-N)	NO_2 (mg/L-N)	Total PO_4 (mg/L-P)	TDS (mg/L)
I123 08-14	—	—	265, 265	0.8, 0.8	<0.10, <0.10	6.0, 6.0	250, 270
B1E 08-14	—	<2, <2	<1, <1	280, 300, 300	<0.10, <0.10	—	2,985, 3,000
B2E 08-14	—	<2, <2	<1, <1	260, 270, 300, 280, 320	0.33, 0.33, 0.34, 0.34, 0.34	—	3,200, 3,175
B3E 08-14	—	<2, <2	<1, <1	260, 310, 290	<0.10, <0.10	—	3,145, 3,160
I123 08-28	96, 96	36, 36	—	—	0.20, 0.20, 0.20, 0.20, 0.21	2.4, 2.6	—
B1E 08-28	23, 22	3, 3	—	—	—	—	—

(continued)

TABLE L-5. (continued)

Sample Identification	Total Alkalinity (mg/L-CaCO$_3$)	TOC (mg/L-C)	NH$_3$ (mg/L-N)	NO$_3$ (mg/L-N)	NO$_2$ (mg/L-N)	Total PO$_4$ (mg/L-P)	TDS (mg/L)
B2E 08-28	28, 28	<2, <2	—	—	—	—	—
B3E 08-28	27, 28	—	—	—	—	—	—
B3E 08-31	—	—	<1, <1	—	—	—	—
I123 09-07	103, 103	—	—	—	—	—	—
I123 09-08	—	—	238, 238	3.4/3.6	—	5.6, 5.6	—
B1E 09-08	—	3, 3	—	250, 265	—	—	—
B2E 09-08	—	3, 3	—	270, 275	—	—	—
B3E 09-08	—	4, 4	—	270, 263	—	—	—

(continued)

TABLE L-5. (continued)

Sample Identification	Total Alkalinity (mg/L-CaCO$_3$)	TOC (mg/L-C)	NH$_3$ (mg/L-N)	NO$_3$ (mg/L-N)	NO$_2$ (mg/L-N)	Total PO$_4$ (mg/L-P)	TDS (mg/L)
I123 09-05	—	29, 29	258, 250, 250	270, 315	—	—	—
B1E 09-05	—	—	<1, <1	—	—	—	—
B1E 09-18	—	3, 3	<1, <1	280, 285	—	—	—
I123 09-21	47, 47	42, 42	—	—	—	—	—
B1E 09-21	38, 38	2, 3	—	285, 285	—	—	—
B2E 09-21	18, 18	3, 3	—	275, 275	—	—	—
B3E 09-21	37, 37	2, 3	—	290, 290	—	—	—
B3E 09-26	—	2.2, 2.5	0.14, 0.15, 0.16[a]	275, 275	0.27, 0.27	—	—

(continued)

TABLE L-5. (continued)

Sample Identification	Total Alkalinity ($mg/L-CaCO_3$)	TOC (mg/L-C)	NH_3 (mg/L-N)	NO_3 (mg/L-N)	NO_2 (mg/L-N)	Total PO_4 (mg/L-P)	TDS (mg/L)
B3E 10-06	—	7, 8	0.25, 0.25, 0.25[a]	270, 272	<0.10, <0.10	—	—
I3 10-06	—	42, 40	258, 258	—	—	—	—
I123 10-24	32, 32	35, 34	—	—	—	—	—
I123 10-23	—	36, 41, 45, 44	—	—	—	—	—
BE3 10-11	—	5, 5	0.05, 0.05[a]	285, 285	—	—	—
I12 11-01	—	34, 38.5, 38, 39, 34	250, 250	—	0.14, 0.14	—	—

(continued)

TABLE L-5. (continued)

Sample Identification	Total Alkalinity (mg/L-CaCO$_3$)	TOC (mg/L-C)	NH$_3$ (mg/L-N)	NO$_3$ (mg/L-N)	NO$_2$ (mg/L-N)	Total PO$_4$ (mg/L-P)	TDS (mg/L)
BE3 10-26	—	3, 3	—	—	<0.10, <0.10	—	—
BE3 11-01	40, 40	3, 3	265, 265	—	<0.10, <0.10	—	—
BE3 10-29	28, 27, 28, 28	—	—	14, 14.9	—	—	—
BE1 11-07	—	—	—	270, 285	0.31, 0.31	—	2,990, 2,955
BE3 11-17	53, 53	10, 10	300, 295, 290, 290	—	—	—	—
I12 11-28	—	36, 36	268, 270	—	—	—	—
BE1 11-28	—	2, 2	<1, <1	270, 270	—	—	—

(continued)

TABLE L-5. (continued)

Sample Identification	Total Alkalinity (mg/L-CaCO$_3$)	TOC (mg/L-C)	NH$_3$ (mg/L-N)	NO$_3$ (mg/L-N)	NO$_2$ (mg/L-N)	Total PO$_4$ (mg/L-P)	TDS (mg/L)
BE2 11-28	—	2, 2, 2, 2, 2	<1, <1	270, 270	—	—	—
I12 11-25	267, 265 260, 260	33, 33	—	—	—	—	—
BE1 11-25	42, 41	2, 2	—	—	—	—	—
BE2 11-25	38, 38	2, 2	—	—	—	—	—

a Technicon automated method for NH$_3$ analysis.

TABLE L-6. LABORATORY QUALITY CONTROL DUPLICATE SAMPLES FOR RESIDUE ANALYSIS

Sample Identification	TSS (mg/L)	VSS (mg/L)
MLB1 08-15	2730, 2750	2240, 2220
MLB2 08-15	3570, 3520	2910, 2920
MLB3 08-15	4620, 4540	3770, 3710
MLB1 09-05	2680, 2690	2060, 2060
MLB2 09-05	3650, 3700	2860, 2920
MLB3 09-05	4640, 4600	3680, 3640
I123 09-23	1.3, 2.0	1.0, 1.7
MLB1 09-23	2440, 2590	1980, 2060
MLB2 09-23	3540, 3610	2790, 2880
MLB3 09-23	4690, 4700	3620, 3700
B1E 09-23	10, 11	7, 8
B2E 09-23	11, 12	7, 8
B3E 09-23	13, 12	8, 10
MLB3 10-03	4320, 4430	3430, 3500
MLB3 11-14	4210, 4230	2500, 2510
I1 11-22	5, 5	2, 2
I2 11-22	155, 157	21, 23
B1E 11-22	9, 9	4, 3
B2E 11-22	30, 30	18, 18
MLB1 11-22	3040, 3060	2900, 2920
MLB2 11-22	8790, 8930	3190, 3240

Exceptions to the aforementioned laboratory quality control practices (duplicate/replicate analyses) are:

- the analysis of sample parameters which were usually reported as less than the minimum detectable limit for accuracy, and
- the analysis of oxygen uptake rate and zone settling velocity (ZSV).

A randomly selected sampling of the COD laboratory quality control results is presented in Table L-7. In addition to the duplicate analyses of COD samples analyzed during the study, blind standards were also analyzed as well as sample spikes in order to check analyst performance.

In the early portion of the study, most QA/QC samples were analyzed using the method of known addition and/or serial dilution (recovery tests). This quality control practice was repeated for some parameters throughout the study. A randomly selected sampling of these data is presented in Table L-8 for the parameters NH_3, total P, TOC, NO_2, and NO_3. If an interfering ion was suspected, the samples would be routinely pretreated for removal of suspected interferences.

The quality assurance / quality control data indicate that all analytical observations are accurate within acceptable statistical deviations. Therefore, the data are adequate for use in developing design criteria for the autotrophic biological treatment process.

TABLE L-7. LABORATORY QUALITY CONTROL FOR CHEMICAL OXYGEN DEMAND ANALYSIS

Sample Identification		Concentration (mg/L)		
			Blind Standard	
		Duplicate, Replicates[a]	True	Observed
I123	08-14	220, 226	-	-
B1E	08-14	12, 16, 24	-	-
B2E	08-14	8, 4, 12	-	-
B3E	08-14	45, 53	-	-
B3E	09-12	9, 13	-	-
TOC[b]	09-07	-	125	123, 137
TOC	09-08	-	125	121
TOC	09-10	-	150	130
TOC	09-11	-	150	150, 166
TOC	09-13	-	25	28
TOC	09-14	-	25	23
TOC	09-14	-	250	248
TOC	09-20	-	225	229
TOC	09-21	-	250	243
TOC	09-27	24, 26, 22, 27	25	22 - 27
B3E(BD)[c]	09-28	34, 38	30[d]	34 - 38
TOC	10-04	-	125	127
TOC	10-05	-	175	191
TOC	10-06	-	125	124
TOC	10-06	-	175	202
TOC	10-11	-	25	28
TOC	10-13	-	25	19
TOC	09-28	-	12.5	12
B3E	10-17	10, 9	-	-
I3	10-17	172, 174	-	-
B3E	10-21	50, 51	-	-
TOC	10-22	-	250	253
TOC	11-03	-	250	258
B2E	11-22	46, 34	-	-

[a] Randomly selected samples from data results.

[b] Samples containing blind standard are labeled TOC.

[c] Blind duplicate.

[d] Theoretical value based on observed B3E 09-28 value for organic carbon.

TABLE L-8. RECOVERY TEST FOR IMPACT OF INTERFERENCES

		Concentration (mg/L)	
Parameter	Sample Identification	Theoretical	Observed
NH_3 (mg/L-N)	100% I123, 08-14	-	51
	25% I123 + 75% 25 mg/L-N	31.5	31.5
	50% I123 + 50% 25 mg/L-N	38	38
	75% I123 + 25% 25 mg/L-N	44.5	45
	20% B3E, 11-12	-	51
	10% B3E, 11-12	27	27
	100% B2E, 11-12	-	<1
	50% B2E + 50% 10 mg/L-N	<5.0	4.6
	25% B2E + 75% 10 mg/L-N	<7.5	7.0
Total PO_4 (mg/L-P)	100% I123, 08-28	-	2.4
	50% I123, 08-28	1.2	1.3
TOC (mg/L-C)	100% I12, 11-28	-	36
	75% I12, 11-28	27	27
	100% B3E, 10-27	-	2
	50% B3E + 50% 6.0 mg/L-C	6.0	5.9
NO_2 (mg/L-N)	100% B3E, 11-01	-	<0.1
	50% B3E, 11-01	<0.10	<0.1
NO_3 (mg/L-N)	100% I123, 09-26	-	0.5
	50% I123, 09-26	<0.5	<0.5
	25% I123, 09-26	<0.5	<0.5
	100% B2E, 08-21	-	284
	50% B2E, 08-21	142	135
	100% B3E, 10-29	-	14
	50% B3E, 10-29	7.0	7.45
	100% I123, 10-02	-	1.0
	25% I123 + 75% 1.0 mg/L-N	1.0	1.1

APPENDIX M

KRW-PDU WASTEWATER COLLECTION ANALYTICAL RESULTS

A schematic of the KRW-PDU is presented in Figure M-1. The wastewater from this process is produced during cooling of the raw product gas. After leaving a cyclone the raw product gas is quenched in a quench scrubber, then further cooled and scrubbed with water in a packed-bed cooler (product gas cooler). Most of this gas is routed to a thermal oxidizer. A portion of the gas is further scrubbed and cooled in a second packed-bed gas cooler before being recycled back to the gasifier. Scrubber and cooler waters are also recycled. The water blowdown from each of these units is depressurized and routed to a separator pit, where solids are removed. Waters from the separator are returned to the quench unit and coolers, and excess water is routed to wastewater storage tanks (and subsequently disposed off site). The two wastewaters used in the biological treatability study were the quench scrubber water recycle (R-12) and the product gas cooler water recycle (R-15). These streams were combined on the basis of a one-to-one composite.

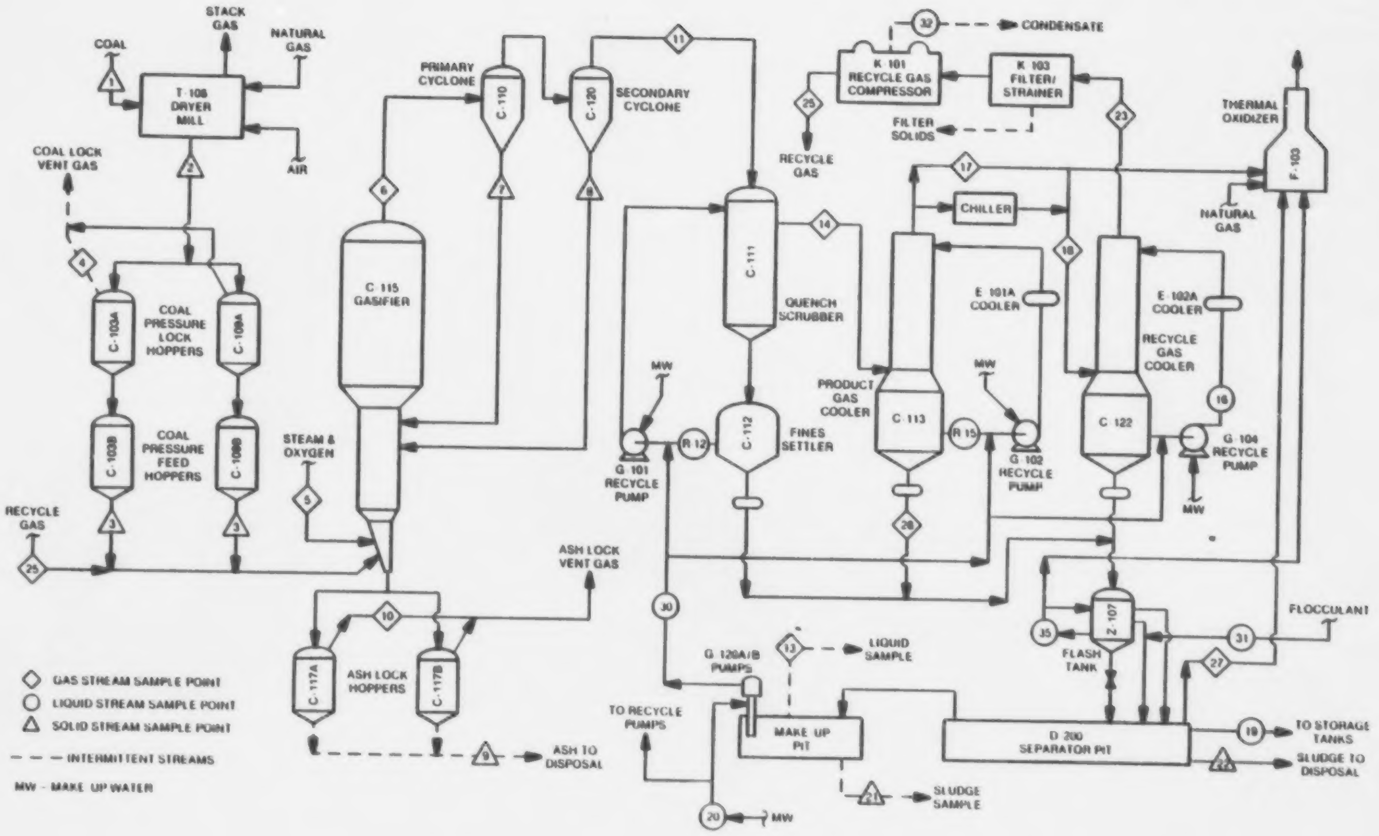
COAL
1
STACK GAS
NATURAL GAS
T-108 DRYER MILL
AIR
2
COAL LOCK VENT GAS
4
C-103A
C-108A
COAL PRESSURE LOCK HOPPERS
C-103B
C-108B
COAL PRESSURE FEED HOPPERS
3
3
RECYCLE GAS
25
STEAM & OXYGEN
5
6
C-115 GASIFIER
PRIMARY CYCLONE
C-110
7
C-120
SECONDARY CYCLONE
8
11
10
ASH LOCK VENT GAS
C-117A
C-117B
ASH LOCK HOPPERS
9
ASH TO DISPOSAL
GAS STREAM SAMPLE POINT
LIQUID STREAM SAMPLE POINT
SOLID STREAM SAMPLE POINT
INTERMITTENT STREAMS
MW - MAKE UP WATER
C-111
QUENCH SCRUBBER
14
MW
G-101 RECYCLE PUMP
R 12
C-112
FINES SETTLER
30
G-120A/B PUMPS
13
LIQUID SAMPLE
TO RECYCLE PUMPS
MAKE UP PIT
21
SLUDGE SAMPLE
20
MW
32
CONDENSATE
K-101 RECYCLE GAS COMPRESSOR
K-103 FILTER/ STRAINER
25
RECYCLE GAS
FILTER SOLIDS
23
17
CHILLER
PRODUCT GAS COOLER
C-113
28
R 15
MW
G-102 RECYCLE PUMP
E-101A COOLER
18
E-102A COOLER
RECYCLE GAS COOLER
C-122
16
G-104 RECYCLE PUMP
MW
THERMAL OXIDIZER
F-103
NATURAL GAS
Z-107
FLASH TANK
35
31
FLOCCULANT
27
D-200 SEPARATOR PIT
19
TO STORAGE TANKS
22
SLUDGE TO DISPOSAL

Figure M-1. PDU wastewater sampling locations

TABLE M-1. WATER QUALITY ANALYSIS OF SAMPLES COLLECTED AT R-12 DURING BULK WASTEWATER COLLECTION

Parameter[a]	Sample[b] / Time of Collection				
	1051	1310	1510	1925	Composite
pH (pH units)	7.04	6.62	6.71	6.73	
Conductivity (umhos/cm)	4,890	4,700	4,810	4,100	
NH_3-N	520	540	530	540	
$S^=$	58	56	63	57	
$SO_3^=$	5	8	6	6	
SCN^-	130	140	130	140	
Total alkalinity as $CaCO_3$					700
TOC					190
TIC					220
COD					340
Cl^-					670
F^-					42
Total CN^-					74

(continued)

TABLE M-1. (continued)

Parameter[a]	Sample[b] / Time of Collection				
	1051	1310	1510	1925	Composite
Free CN^-					6
Nitrate					1.7
Phenol					0.03
Phosphate					0.08
Formate					78
TDS					1,410
TSS					99
Nitrite					<0.02

[a] All results as mg/L except where indicated.

[b] Collected on 6/21/83.

TABLE M-2. WATER QUALITY ANALYSIS OF SAMPLES COLLECTED AT R-15 DURING BULK WASTEWATER COLLECTION

	Sample[b] / Time of Collection				
Parameter[a]	**1315**	**1510**	**1915**	**2125**	**Composite**
pH (pH units)	6.86	7.05	7.24	6.93	
Conductivity (umhos/cm)	7,500	7,500	8,500	7,900	
NH_3-N	1,040	1,050	1,020	1,010	
$S^{=}$	130	130	140	140	
$SO_3^{=}$	4	5	6	6	
SCN^-	19	25	24	19	
Total alkalinity as $CaCO_3$					3,100
TOC					125
TIC					980
COD					460
Cl^-					60
F^-					4.2
Total CN^-					65
Free CN^-					52

(continued)

TABLE M-2. (continued)

	Sample[b] / Time of Collection				
Parameter[a]	1051	1310	1510	1925	Composite
Nitrate					2.5
Phenol					0.22
Phosphate					<0.05
Formate					16
TDS					60
TSS					650
Nitrite					<0.02

[a] All results as mg/L except where indicated.

[b] Collected on 6/21/83.

TABLE M-3. WATER QUALITY OF SAMPLES ANALYZED AFTER SHIPMENT TO RADIAN

Parameter[a]	Samples[b]	
	R-12	R-15
pH (pH units)	6.71	7.19
Conductivity (umhos/cm)	4,980	8,090
NH_3-N	505	970
SCN^-	150	54
$SO_3^=$	20	36
$S^=$	110	190
TCN^-	NA[c]	NA[c]
FCN^-	NA[c]	NA[c]
TOC	100	120

[a] All results as mg/L except where indicated.

[b] Samples collected from wastewater drums on June 30, 1983.

[c] Not analyzed.